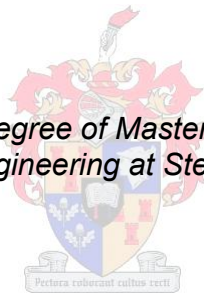


PRE-SIGNAL STUDY AT AN AT-GRADE INTERSECTION WITH SEPARATE RIGHT-TURN PHASE

by
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*Thesis presented for the degree of Master of Engineering (Research) in
the Faculty of Engineering at Stellenbosch University*



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DECLARATION

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ABSTRACT

Capacity waste happens when right-turn vehicles have right-of-way during a separate right-turn phase and lanes (e.g., through lanes) of the same approach of the intersection cannot discharge vehicles during that green phase. Right-turn traffic consumes the capacity which otherwise could be provided to through traffic movements at an at-grade signalized intersection. Therefore, it is widely considered that it would lower intersection capacity and increase total delay (Lin, Machemehl, Lee & Herman, 1984).

The pre-signal strategy proposed in this research is specifically designed to improve this problem. The following aspects of this strategy were studied in this research,

- Capacity benefits of this strategy,
- Relationships between the capacity and the length of sorting area (the area between the two signals),
- Signal timing of both main signal and pre-signal,
- Clearance time of the sorting area,
- Main signal phasing options
- Signal coordination between the main signal and the pre-signal,
- Utilization of the sorting area, and
- Pre-signal strategy performance in a simulated environment.

The results of this study showed that right-turn movement benefits significantly from this pre-signal strategy. For example, right-turn capacity can be doubled if a pre-signal is installed on one through lane of an approach with one right-turn lane.

It was also found, the maximum approach capacity benefit is not affected significantly by the length of the sorting area for a given green period. The optimal green time and the available pre-signal green time for right-turn movement were also derived in this research. Different main signal phasing options were studied and compared. Phasing options which fit the proposed pre-signal strategy were found. Recommended values for right-turn green time of both signals were given based on different lengths of sorting area.

The case study, which compared the performance of some critical movements at the intersection with and without the proposed pre-signal system, confirms the results concluded in this study.

A potential problem with this strategy when applied at a real intersection is that it may confuse drivers. Drivers need to be educated and will need time to get familiar with this signal control method.

OPSOMMING

Beskermde regsdraaifases vir verkeer by gelykvlak seinbeheerde kruisings gebruik die kapasiteit wat benut kon word deur deurbewegings. Dit verlaag interseksie kapasiteit en totale oponthoud verhoog.

Die voorseinstrategie wat in die navorsing studie voorgestel word is spesifiek ontwikkel om die probleem op te los of te verminder. Die volgende aspekte van die strategie is ondersoek in die navorsingsstudie:

- Kapasiteitsvoordele van die strategie.
- Die verhouding tussen die kapasiteit en die lengte van die sorteringsarea (die area tussen die twee seine).
- Seintydstoedeling van beide die hoofseinfase en die voorseinfase.
- Ontruimingstyd van die stoorarea.
- Hoofseinfaseopsies.
- Seinkoördinasie tussen die hoofsein en die voorsein.
- Benutting van die sorterings area, en
- Voorseinstrategieprestasië in 'n gesimuleerde omgewing.

Die resultate bewys dat die regsdraaibeweging grootliks bevoordeel word nadat die voorseinstrategie ingestel is. Byvoorbeeld, regsdraaikapasiteit kan verdubbel word as 'n voorseinfase ingestel word op een van die deurlane tesame met 'n enkele regsdraailaan.

Daar is ook gevind dat die kapasiteit nie grootliks beïnvloed word deur die lengte van die stoorgebied nie. Die optimale groentyd en die beskikbare voorsein groen tyd vir die regsdraaibeweging is ook afgelei in die navorsing. Verskillende hoofseinfaseopsies is bestudeer en vergelyk. Faseringsopsies vir die voorgestelde voorseinstrategie is gevind. Voorgestelde waardes vir regsdraaigroentyd van voorseine en hoofseine is bereken om kapasiteit te verbeter, gebaseer op verskillende lengtes van die stoorarea.

Die gevallestudie wat die prestasie op 'n aanloop met en sonder die voorgestelde voorseinstrategie vergelyk, bewys resultate wat ooreenstem met die bevindinge in die studie.

Die verwagte probleem met die voorseinstrategie, wanneer dit ingestel word by 'n werklike interseksie, is verwarring van die bestuurders. Bestuurders sal opgevoed moet word en sal tyd nodig hê om gewoond te raak aan die voorseinmetode.

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LIST OF ABBREVIATIONS

PO	protected-only
PPLT	protected/permissive left-turn
CFI	continuous flow intersection
Pc/h/ln	passenger cars/hour/lane
DDI	diverge diamond interchange
U.K.	United Kingdom
veh/h	vehicle per hour
veh/h/approach	vehicle per hour per approach
sec/veh	second per vehicle
HCM	Highway Capacity Manual
TRB	Transportation Research Board
VMS	variable-message sign
LT	left-turn
TH	through

LIST OF VARIABLES

Some variables in CHAPTER 4 are listed here.

C_m = cycle length of the main signal (s)

C_p = cycle length of the pre-signal signal (s)

e = extension of effective green (s)

E_r = effective green time for right-turn vehicles (s)

g_r = green time of pre-signal for right-turn movement (s)

G_r = main green for right-turn movement (s)

G_t = main green for through movement (s)

h_s = saturation headway (s)

i = total number of vehicles passing the main stop line during G_r

i_G = number of vehicles that could be served during G_r in a right-turn lane

i_n = the part of i_G queuing after the no stopping area in one right-turn lane

i_N = number of the vehicles could be accommodated in a sorting area

i_r = pre-signal change intervals for right-turn vehicles(s)

i_t = pre-signal change intervals for through vehicles(s)

I_r = main signal change intervals for right-turn vehicles (s)

I_t = main signal change intervals for through vehicles (s)

l_1 = total start-up lost time (s)

L = length of the sorting area (m)

L_e = length of the wasted space in sorting area (m)

n = number of right-turn lanes

N = number of lanes in sorting area

q_{rc} = right-turn capacity under conventional signal option ($\frac{veh}{h}$)

q_{rp} = right-turn capacity under pre-signal option ($\frac{veh}{h}$)

Δq = capacity benefited from installing a pre-signal ($\frac{veh}{h}$)

Δq_{max} = maximum capacity benefited from installing a pre-signal ($\frac{veh}{h}$)

r_{ct} = red clearance time of the pre-signal through phase (s)

r_{ct} = red clearance time of the pre-signal through phase (s)

R_{ct} = red clearance time of the main through phase (s)

R_r = right-turn phasing length on the crossing road (s)

R_t = through phasing length on the crossing road (s)

S = average jam spacing (m/veh)

t_{cr} = sorting area clearance time for right-turn vehicles (s)

t_{ct} = sorting area clearance time for through vehicles (s)

t_m = minimum green required to clear a full sorting area (s),

v_l = speed limit of the road (m/s)

\bar{v}_r = average clearance speed of the last right-turn vehicle (m/s)

\bar{v}_t = average clearance speed of the last through vehicle (m/s)

y_r = yellow interval of the pre-signal right-turn phase (s)

Y_r = yellow interval of the main right-turn phase (s)

α = ratio of main green time to cycle length

CHAPTER 1 INTRODUCTION

1.1 Background

Dealing with right-turn traffic is always a challenge at an at-grade intersection in a left-hand driving country. The assignment of right-of-way between right-turn traffic and the opposing traffic cause safety problems, reduce capacity of the intersection and increase total delay.

When compared to permissive right-turn phasing, protected right-turn phasing may give an intersection higher capacity to deal with right-turn traffic by providing storage bay and protected phase. It eliminates the conflicts and improves right-turn safety. Right-turners do not need to wait for gaps and have right-of-way in their phase.

However, separate right-turn phasing increases total delay for an intersection (Agent and Deen, 1978) since it is done at the expense of the amount of green time available for through traffic. It may also reduce the total capacity of an intersection.

Traditional separate right-turn phasing on an approaching leg of an intersection wastes capacity because neither through lanes discharge vehicles during the green time for right-turn vehicles, nor right-turn lanes/bays discharge vehicles during the green time for through movements of the same approach. To solve this problem, Xuan, Daganzo & Cassidy (2011) proposed a pre-signal concept in an effort to make more lanes discharge vehicles, thus to increase capacity.

In the pre-signal control strategy, a pre-signal with an additional stop line is applied upstream of an approach to form a sorting area between the pre-stop line and the main stop line (refer to Figure 1.1). Controlled by the pre-signal, through vehicles and right-turn vehicles enter the sorting area in turn during their green phases, using part of or all lanes and waiting to be discharged from the main stop line (left-turn vehicles can also participate in the sorting if necessary). Theoretically, this concept would significantly increase the capacity of an approach with pre-signal control under oversaturated flow conditions (Xuan, 2011; Zhou & Zhuang, 2013).

The pre-signal strategy could be more economical in comparison to land acquisition or upgrading the intersection into an interchange to increase capacity at an at-grade intersection under heavy traffic conditions.

The pre-signal concept is really a new traffic control method for an at-grade intersection. There are limited previous studies focusing on how pre-signals could increase intersection capacity (Xuan *et al.*, 2011; Yan, Jiang & Xie, 2013), and on how the pre-signal concept could be improved by swapping signal phases (Xuan, 2011).

1.2 Problem statement

Pre-signal system could effectively increase the capacity of an approach under heavy traffic flow conditions (Xuan, 2011; Yan *et al.*, 2013). In an oversaturated intersection with limited space to be expanded or to be upgraded into an interchange, pre-signal strategy could be an alternative design which may improve the performance of an intersection as it has lower investment and land requirement. As it is a newly developed concept with limited previous studies and with few actual implementations, research still needs to be done to improve the concept and the theory.

Former pre-signal studies showed that right-turn movements usually have higher benefit ratios when compared to other movements. Based on this fact, the pre-signal strategy proposed in this study is specifically designed for right-turn movements.

Furthermore, some of the disadvantages of the former pre-signal concepts have been improved. The limitations of exit lanes, and the additional stop times that arise because of the installation of pre-signals, are reduced in the proposed strategy. There would also be more phasing options which could fit the proposed strategy than the former ones.

1.3 Concept of the study

Based on the former pre-signal concepts, the concept developed in this study is specifically designed to increase the right-turn capacity and minimize the adverse effect on through vehicles on an approach of an at-grade intersection under separate

right-turn control. For a better understanding, a video footage could be referred to on the following link: <https://www.youtube.com/watch?v=U70mpu9Zd1U>.

1.3.1 Concept

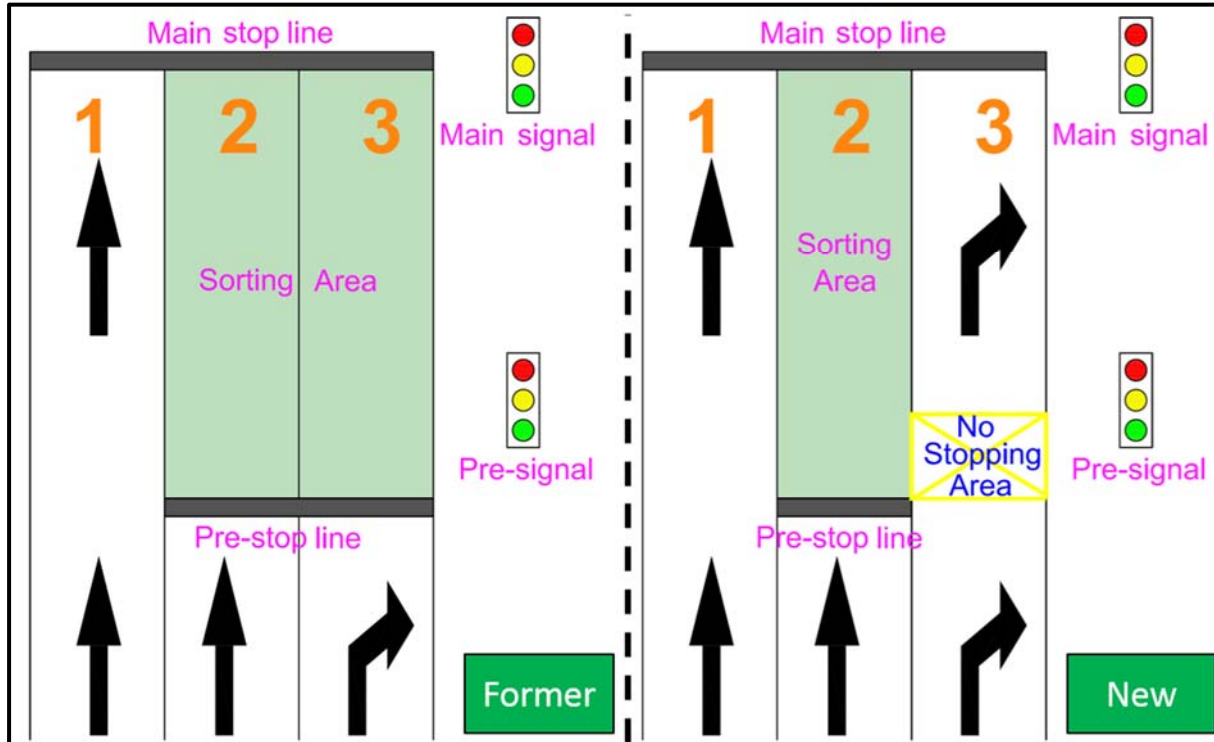


Figure 1.1 Example of Contrast between Former Pre-Signal Concept and the New Concept

In the example of pre-signal concepts shown in Figure 1.1, the sorting area denotes the place located between the main stop line and the pre-stop line. The pre-signal gives right-of-way either to the through vehicles or to the right-turn vehicles to occupy the sorting area. Vehicles should always wait after the pre-stop line before being served by the pre-signal.

In the new concept proposed in this study, the change comes from the right-turn lane. Right-turn lane is not used in the sorting area anymore and right turners therefore, could always proceed ahead in the right-turn lane without holding by the pre-signal. Right turners, however, are still controlled by the pre-signal if they want to use the sorting area (by making lane changes into the sorting area). The no stopping area is designed to prevent queued vehicles blocking right-turn vehicles from entering the sorting area.

Approaches are expected to benefit from installing the proposed pre-signals in terms of right-turn capacity. A more detailed description of the pre-signal concept could be found in Appendix A

1.3.2 Improvements of the concept

The 5 features of former pre-signal concepts listed below are the original concern of developing the pre-signal strategy proposed in this research. For the sake of easy understanding, the features listed below are based on the example shown in Figure 1.1.

1. Right-turn movements usually benefit more

Through volume is normally higher than the turning volume in the same approach of an intersection. This leads to the uneven allocation of facilities (for example, discharging lanes) in an approach, especially for approaches with more than 2 discharging lanes. The extent to which a through movement and a right-turn movement could benefit from a sorting area is always different. For instance, in the example shown in Figure 1.1, the number of discharging lanes for through movement increases from 2 to 3 after installing the pre-signal system, and corresponds to a benefit rate of 50 percent. However, the discharging lanes increases by 100 percent for the right-turn movement (from 1 lane to 2 lanes). In conclusion, right-turn movements could usually have a higher benefit rate than the through movements

2. Number of exit lanes could be a limitation

The main value of the pre-signal strategy comes from the extra lane(s) used to discharge vehicles. This requires more lanes to be available in the exit leg to accommodate the vehicles coming from the extra lanes of the approaching leg. Using Figure 1.1 as an example, if there are only 2 exit lanes (they are enough if no pre-signal are installed) for through movement, the pre-signal system would not be applicable in that case because the number of discharging through lanes increases to 3 after the installation.

3. Increasing stop times

Vehicles usually have to first stop after the pre-stop line and then proceed into the sorting area and stop after the main stop line again. Most of the vehicles using the sorting area have to stop twice.

4. Limited phasing options

The phasing options are limited for the former pre-signal concepts. Both the leading and lagging right-turn phasing option (refer to Figure 4.6 and Figure 4.8) require a long sorting area which may not be available in some intersections with short spacing (Xuan, *et al.*, 2011). Phase swapping option (refer to Figure 4.10) is the only one which was found that could reduce the length of a sorting area (Xuan, 2011; Yan, *et al.*, 2013).

5. Long pre-signal green time required

Pre-signal green time should be enough to fully fill the sorting area. As the example shown in Figure 1.1, the green time of the pre-signal for right-turn vehicles should be enough to “feed” vehicles to all the two lanes in the sorting area to ensure a fully occupied sorting area.

However, for the pre-signal strategy proposed in this research (refer to Appendix A), it has the following features:

1. This pre-signal strategy is specifically designed to handle right-turn vehicles because of the high benefit rate a right-turn movement could get from a pre-signal system
2. The exit lanes for through vehicles are not a limitation anymore because no extra discharging through lane has been added.
3. Only some of the right-turn vehicles using the sorting area would have to stop twice. Right-turn vehicles between the main stop line and no stopping area (refer to Figure 1.1) and through vehicles after the pre-stop line (if the pre-signal and main signal are coordinated well) only have to stop once.
4. As discussed in Section 4.2.4, both the leading right-turn phasing option and the phase swapping option fit the proposed pre-signal strategy in this study. Especially, the leading phasing option has a higher ability to serve the right-turn movement.
5. It needs shorter time to feed the sorting area. Figure 1.1 as an example, the green time of the pre-signal required to fully fill the sorting area in the former

concept (with two sorting lanes) would be twice than that in the proposed concept (with one sorting lane) in this study. This would be critical at some intersections where there is not enough available green time for the pre-signal.

1.4 Aims and objectives of the study

The aims of this research are to analyse the benefit of the proposed pre-signal strategy, and the relationships between capacity and other pre-signal elements in the approach, including length of the sorting area, signal timings and signal coordination. Wasted space in the sorting area is also considered and a South African case study has been presented to indicate how the proposed pre-signal strategy works in a simulated environment. The study could provide some theoretical support structure for the traffic engineers and policy makers who are willing to apply this pre-signal strategy in a real life scenario.

The objectives include to study the:

1. Capacity benefits of this strategy,
2. Relationships between the capacity and the length of sorting area(the area between the two signals),
3. Signal timing of both main signal and pre-signal,
4. Clearance time of the sorting area,
5. Signal coordination between the main signal and the pre-signal,
6. Utilization of the sorting area, and
7. Pre-signal strategy performance in a simulated environment.

1.5 Delimitations of the study

1. It was assumed that the research on left-turn traffic under right-hand driving rules (typically in USA, Europe and China) referenced in this study, can be fully applied to the right-turn traffic under left-hand driving rules as applies in South Africa;
2. It was also assumed that drivers would always like to find a better position when they are going to queue behind the stop line, which means they will

always make a lane change to acquire a closer position to the stop line if there is any vacancy available in the sorting area.

3. Only passenger cars (<6m) were considered in this study for simplicity reasons. Buses and trucks which would affect the characteristics (e.g., start-up lost time, saturation headways) of the discharging flow at signalized intersection were excluded;
4. Left-turn vehicles were not considered when illustrating, describing or analysing the proposed strategy in this study for simplicity reason. Only right-turn and through vehicles used the sorting area.
5. More surveys and data are still needed to support the study of sorting area clearance time.
6. Average values of some elements of a sorting area, including sorting area clearance time, start-up lost time, saturation headway, jam spacing and the extra space in a sorting area, were used in this research. They would not be enough for an approach running under the proposed pre-signal strategy in reality. The 85th percentile values of these elements collected from real sites could be a better choice to ensure better performance in reality.

1.6 Statement

When the word “left” was used in the original research which had been done under the right-turn driving rules, it was changed to “right” after being referenced in this research. In case the word “left” cannot be changed (e.g., in the figures), thereafter a note would be made.

1.7 Research outlines

Following is the structural framework of the study.

- Chapter 1 briefly describes the research background, the current research problems, the concept of the proposed strategy, the research aim and objectives, the research delimitations and the research outlines;
- Chapter 2 presents the theoretical supports for this research;
- Chapter 3 gives the details of the research methodology;
- Chapter 4 presents the analysis and the results of this study;
- Chapter 5 applies the proposed strategy in a simulated environment;

- Chapter 6 concludes the study and suggests some recommendations.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The pre-signal concept is not new for transit systems, which has been used in U.K. since 1990s (Wu, 1998). It was recently proved to be a concept with a potential ability of increasing capacity (especially the turning capacity) of an approach of an at-grade intersection under heavy traffic conditions. However, since it is a relatively new intersection control method, limited research is available on pre-signal theories for general traffic streams and even fewer implementations in reality.

The objective of this research is to study the performance of an approach installed with the proposed pre-signal system. The following aspects are reviewed:

- Right-turn operations
- Pre-signal strategy in transit system
- Pre-signal theory for general traffic
- Signal coordination
- Important elements in pre-signal system
- Lane change

2.2 Right-turn operations

2.2.1 Right-turn lanes or bays

In an intersection where right-turn vehicles do not have the right-of-way against the opposing traffic, even one right-turn vehicle may impede other traffic and cause safety issues (Sampson, Van As, Joubert, Dazeley, Labuschagne & Swanepoel, 2012:5.4). A right-turn lane improves the performance (e.g. capacity, safety and delay) of an intersection by separating right-turn vehicles from the other movements. When arriving at the intersection, right-turn vehicles are stored in right-turn lanes/bays to eliminate the effect of the speed differential between the right-turn movements and through movements and also to eliminate the hindrance while right-turn vehicles waiting for acceptable gaps to finish turning. In South Africa, right-turn lanes or bays will be warranted at most signalized intersection (Sampson *et al.*, 2012:5.4).

2.2.1.1 Functions of right-turn lanes

Right-turn lanes have the following functions (Fitzpatrick, Brewer, Gluck, Eisele, Zhang, Levinson, Zharen, Lorenz, Iragavarapu & Park, 2010:1):

- Reducing conflicts and crashes;
- Separating through, turning, and/or queuing traffic;
- Decreasing delay and increasing capacity;
- Providing operational flexibility and impacts; and
- Providing an area for right-turn vehicles to decelerate outside of the through traffic lane.

2.2.1.2 Warrants

The following factors contribute to the installation of the right-turn lanes (Fitzpatrick *et al*, 2010:1):

- Type/function of roadway,
- Number of lanes,
- Prevailing speeds,
- Traffic control/operations,
- Turn and other volumes,
- Roadway(s) alignment, and
- Safety (conflict, crash numbers, and crash types/causes).

Many right-turn lane warrants had been made based on one or more factors mentioned above.

2.2.1.2.1 Based on queue theory

Based on the queuing theory, Harmelink (1967) proposed some warrants for the need of right-turn lanes at unsignalized intersections, which provided the foundations for many right-turn guidelines in the following decades. The basic assumption of his research was that the probability of the through vehicles blocked by stopped right-turn vehicles should not exceed the threshold values which were given according to different design speeds and operating speeds. Advancing volume, opposing volume, operating speed, percentage of right-turn vehicles are the values needed before using his graphs. An example of his graphs is shown in Figure 2.1.

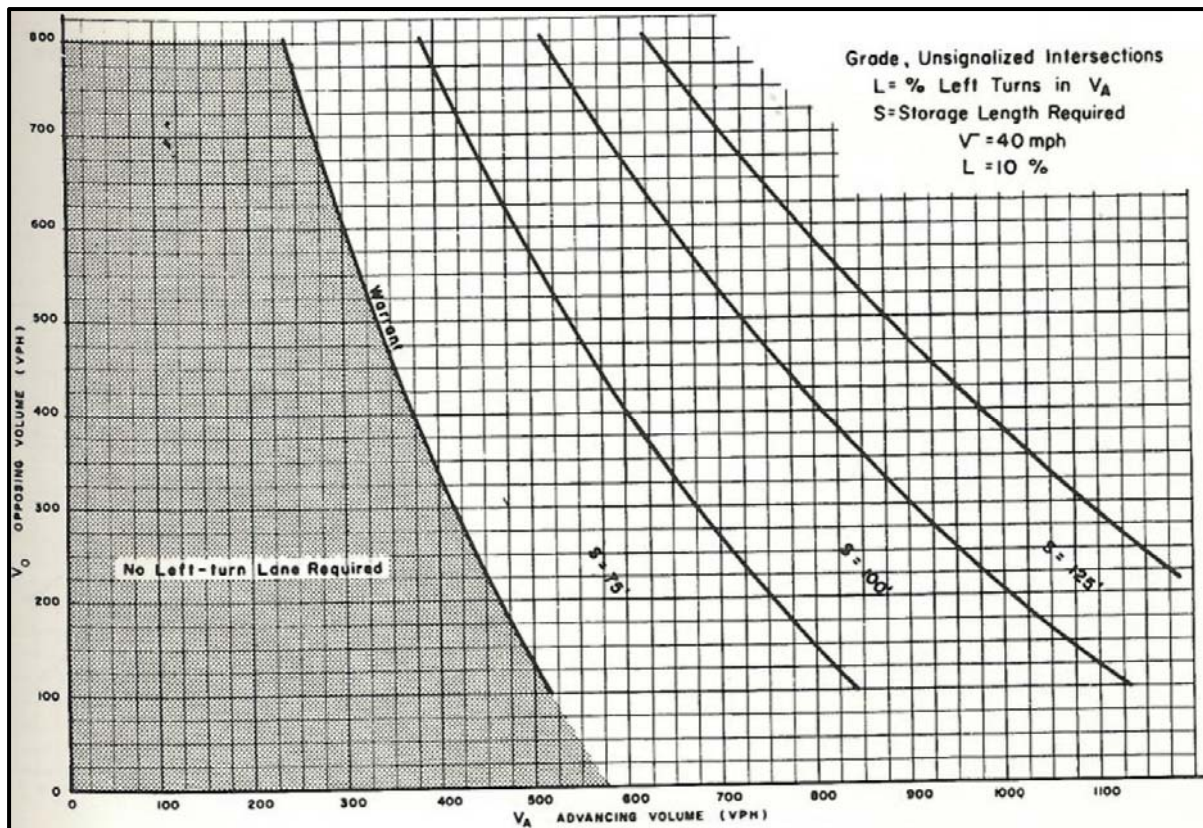


Figure 2.1 Warrant for Right-Turn Storage Lanes on Two-Lane Highways (Harmelink, 1967)

Note: the words “left” in the figure could be converted to the side of “right” under a left-hand driving rule.

2.2.1.2.2 Based on approaching volume

Based on approaching volumes, Koephe and Levinson (1992:98) stated that in most cases, the criteria for providing separate right-turn lanes at unsignalized intersections is when the turning volume is more than 12 vehicles per hour. For intersections with right-turn volume exceeding 300 veh/h during the peak period in South Africa, double right-turn lanes could be warranted (Sampson *et al.*, 2012:5.5).

2.2.1.2.3 Based on safety

Regardless of the capacity improvements, in many cases, right-turn lanes can be provided based on safety benefits alone because the disruptions which can be caused by even a small amount of right-turn vehicles lead to accidents (Sampson *et al.*, 2012:5.5), even when there are sufficient capacity available at those intersections.

In South Africa, right-turn lanes or bays should be warranted at most signalized intersection (Sampson *et al.*, 2012:5.5). For those intersections with lower operating

speeds (<50 km/h) or fewer conflicts between right-turn and other movements, cost-benefit analysis could be conducted before making decisions.

2.2.1.3 Design of right-turn lanes or bays

2.2.1.3.1 Layout

There are a few layouts of approaches designed with right-turn lanes/bays.

1. Approach without constructed median

For an approach without construction median, the right-turn bay could be designed by narrowing lanes of that approach. Figure 2.2 and Figure 2.3 presents two methods (with or without painted island) which could be applied in this case.

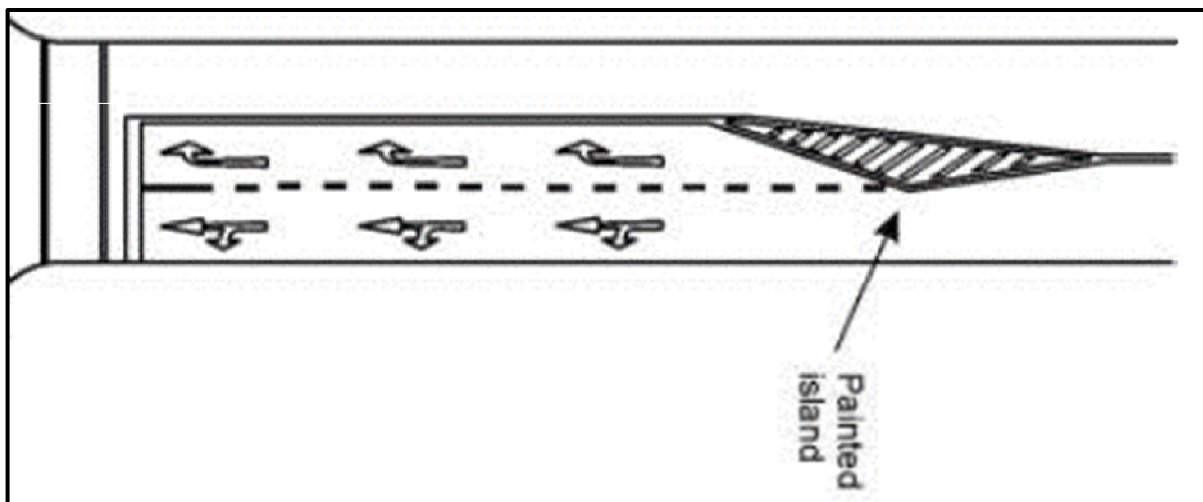


Figure 2.2 Right-Turn Bay with Painted Island (Sampson *et al.*, 2012:5.6)

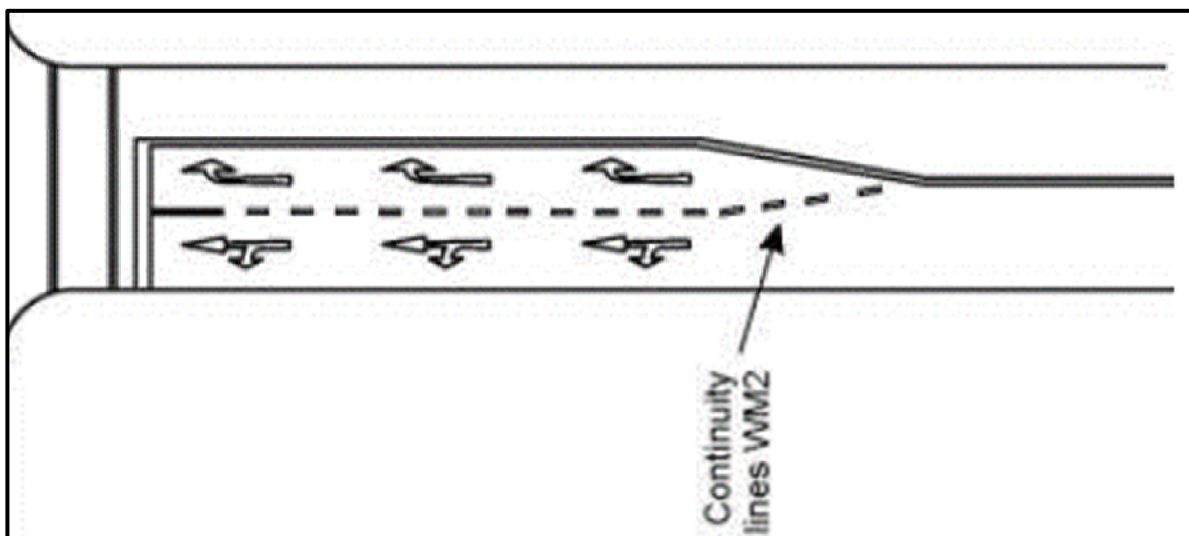


Figure 2.3 Right-Turn Bay without Painted Island (Sampson *et al.*, 2012:5.6)

The painted island as shown in Figure 2.2 could provide great protection to the right-turn movements. However, it forces right turners to steer wheels to the left then to the right before entering the right-turn bay.

The method used in Figure 2.3 could be enough for the intersections in urban areas where street lights are available in the night and speeds are relatively low.

2. Approach with constructed median

Right-turn bay could be added into an approach without narrowing other lanes in the situation where constructed median is available. Part of the median near the intersection could be used to build the right-turn bay. A typical layout for this case could be found in Figure 2.4.

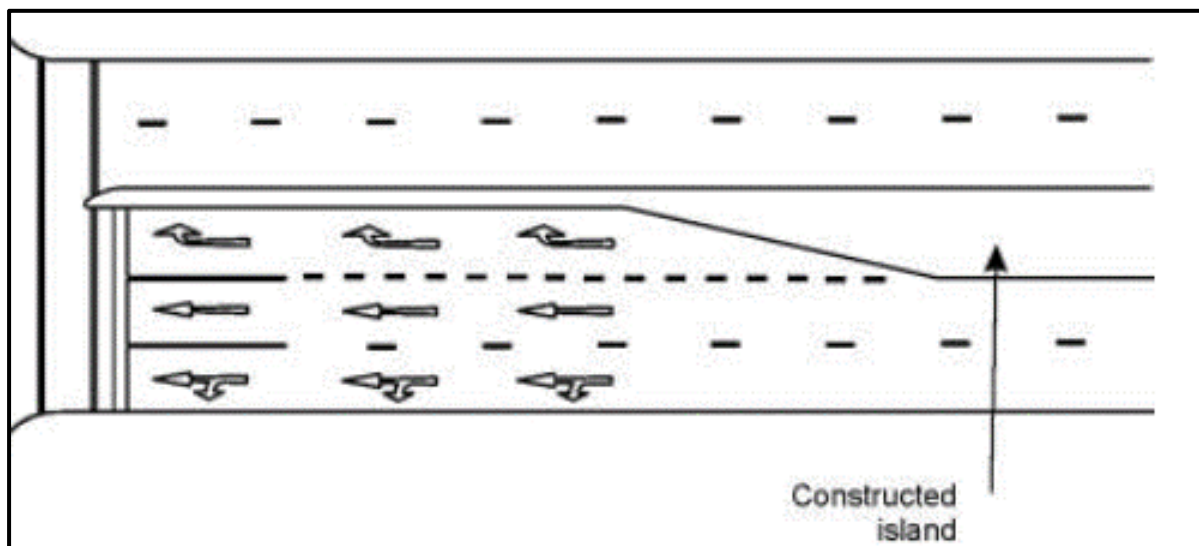


Figure 2.4 Right-Turn Bay Using Part of the Median (Sampson *et al.*, 2012:5.6)

In some cases, right-turn sight distance could be restricted by the opposing queued right-turn vehicles and the wide median. A head-on collision would be a potential hazard for these right turners. Therefore, right-turn bay could be designed in the median to ensure a sufficient sight distance as shown in Figure 2.5.

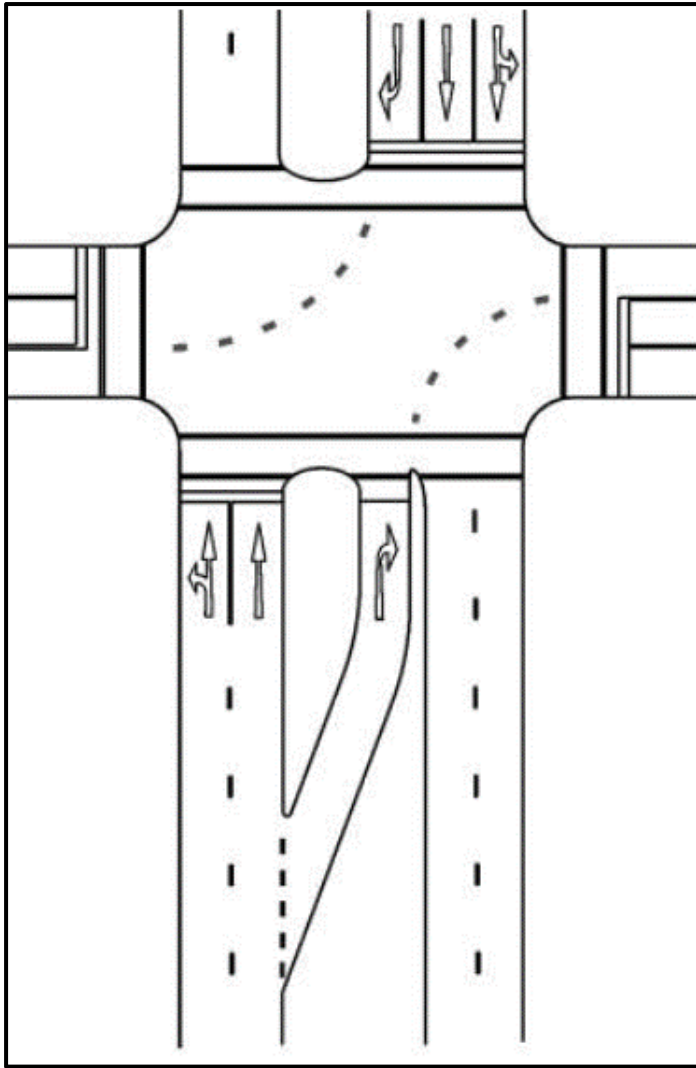


Figure 2.5 Right-Turn Bay Built in Median (Sampson *et al.*, 2012:5.7)

2.2.1.3.2 Right-turn bay length

The turn bay length is described by the HCM 2010 (TRB, 2010) as:

- the length of lane with full width;
- the length of lane where queued vehicles could be stored;
- the length is measured parallel to the roadway centre line; and
- the average value should be applied if there are more than one lane in the bay.

As presented in Figure 2.6, insufficient right-turn bay length causes 1) right-turn vehicle overflow which would block the through lane; 2) through vehicles blockage which would block right-turn vehicle from entering the turning bay. Therefore, right-turn bay length should be well analysed before the construction.

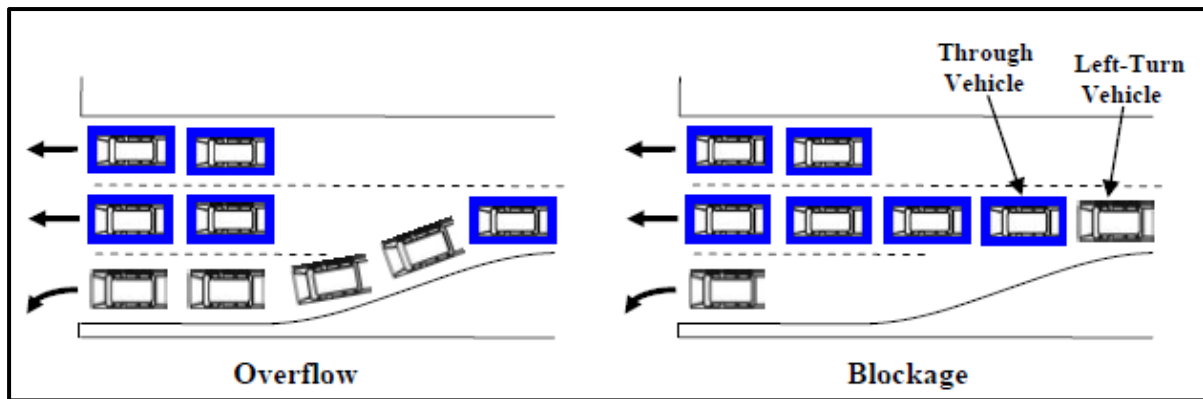


Figure 2.6 Right-Turn Overflow and Blockage Problems (Yu, Qi, Yu, Guo & Chen., 2008)

Note: the words and sides of “left” in this figure could be converted to the sides of “right” under a left-hand driving rule.

Instructions for both signalized and unsignalized intersections were recommended by AASHTO Green Book (AASHTO, 2001:719). For unsignalized intersections, the bay length may be given on the basis of the average arriving rate of turning vehicles in a two-minute period within the peak hour. The minimum space which could accommodate two passenger cars should be provided and it increases as the truck rate increase. For signalized intersections, the storage bay should be designed on the basis of design volume and should consider the heavy traffic surges in some extreme cases. The space which could accommodate 1.5 to 2 times the average stored vehicles per cycle should be provided.

Simulation based methods were also used to determine the turning bay length (Qi, Guo, Y & Teng, 2012). The bay length was estimated by dividing it into two parts, which were storage length and deceleration length. Four traffic simulation models (HCS+, Synchro, SimTraffic and VISSIM) were selected to estimate the storage length and the results were compared with the data collected from 7 intersections. The SimTraffic model was found to be the most accurate one.

In South Africa, the recommended bay lengths given by South Africa Traffic Signs Manual Volume 3 (2012:5.5) were on a basis of expected 95th percentile queue length during peak hours. Attention should also be paid to the queue on the adjacent through lane to ensure the turning vehicles would not be blocked from preceding the turning bay. Furthermore, deceleration length (refer to Figure 2.7) would be required to ensure safety in the situation where vehicles running at high speeds. In conclusion, minimum storage length of 12 metres which could accommodate two

passenger cars should be provided. Generally, typical bay length is between 30 (at least 5 passenger cars) to 60 metres (Sampson *et al.*, 2012:5.8).

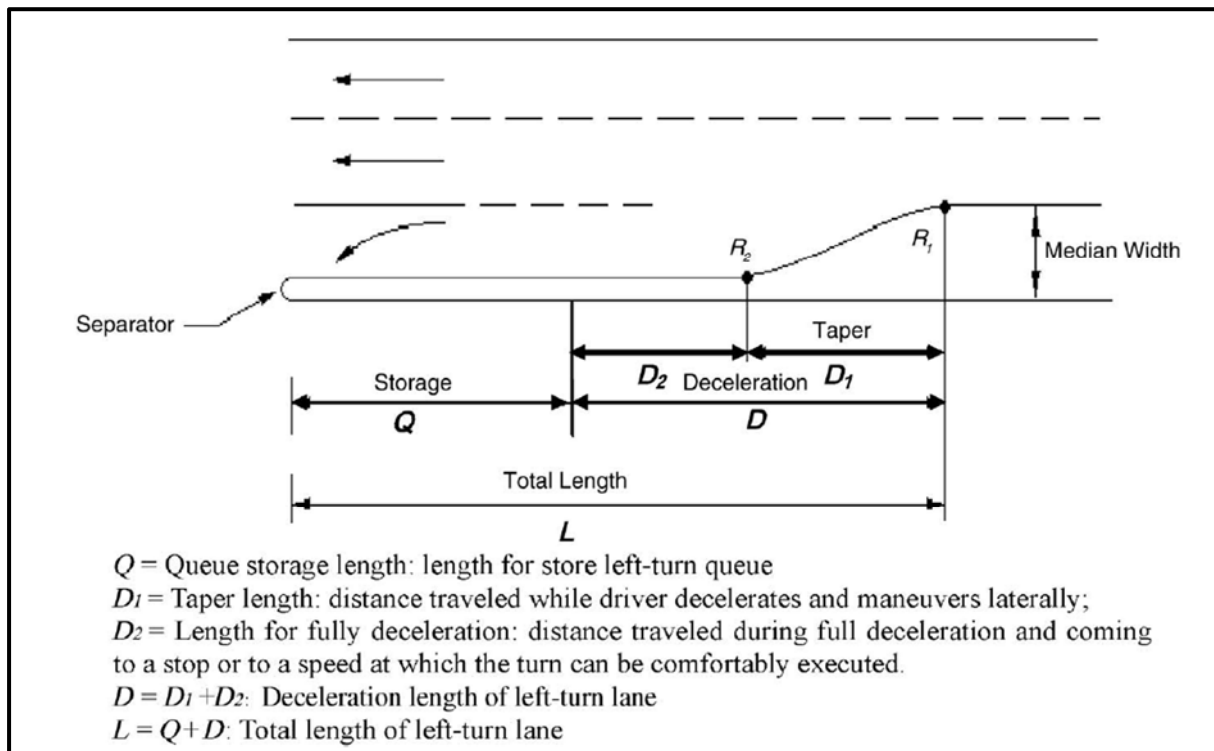


Figure 2.7 Composition of Right-Turn Bay

Note: the words and sides of "left" in this figure could be converted to the sides of "right" under a left-hand driving rule.

2.2.2 Banned right turns

Generally, when compared to the right-turn vehicles, through vehicles are higher in volume and served with more resources at intersections. Thus, when the right-turn vehicles have the right-of-way (e.g., protected phase) to pass the conflict points at a signalized intersection, the output per unit time of the intersection during that period is usually lower than that when the intersection serves the through vehicles. In other words, right-turn vehicles fail to use the intersection as effectively as through vehicles in a green time unit. This leads the right-turn movements to be banned at some intersections with heavy through volume and light turning volume. Some of these treatments are reviewed below.

2.2.2.1 Median U-turn

Right-turn movements were banned in the approaches of intersections designed with median U-turn as shown in Figure 2.8 (Bared & Kaisar, 2002). On an median U-turn designed approach, right turners have to keep right and drive with the through vehicles, then make a U-turn where median U-turn was provided downstream of the intersection. This treatment reduced conflict points (refer to Figure 2.9) when compared to a conventionally designed intersection.

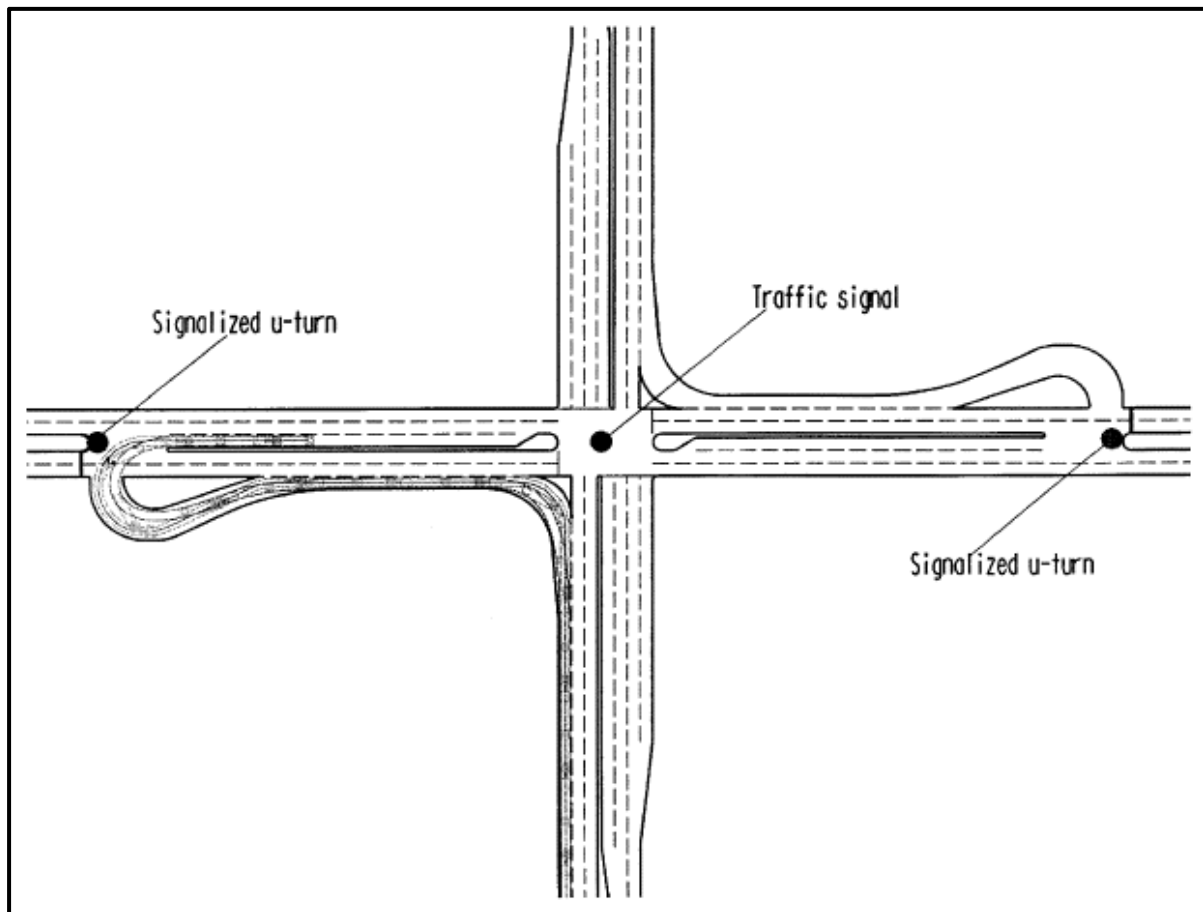


Figure 2.8 Typical Median U-turn Treatments (Bared & Kaisar, 2002)

Note: the sides of "left" in this figure could be converted to the sides of "right" under a left-hand driving rule.

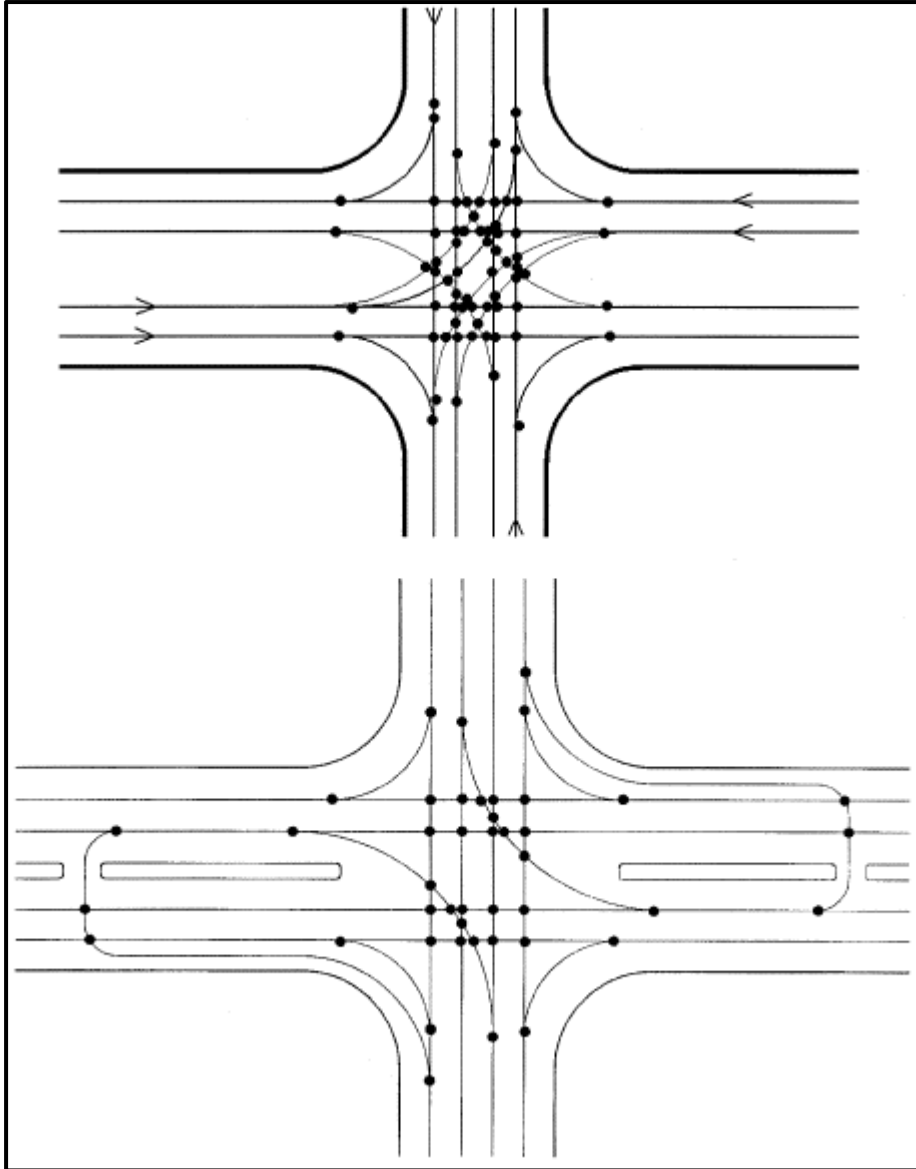


Figure 2.9 Comparison of the Potential Conflict Points between Conventional Strategy (68 Points) and the Median U-Turn Strategy (44 Points) (Bared & Kaisar, 2002)

Note: the sides of "left" in this figure could be converted to the sides of "right" under a left-hand driving rule.

In an effort to study the capacity of the turning movement using U-turn, Al-Masaeid (1999) developed two formulas based on regression analysis using data collected from 7 median U-turn sites in Jordon,

$$C = 799 - 0.31 * q_c \quad (1)$$

$$C = 1545 - 790 * e^{q_c/3600} \quad (2)$$

Where,

$C = \text{capacity of } U - \text{turn movement} \left(\frac{PCU}{h} \right), \text{ and}$

$q_c = \text{conflicting traffic flow} \left(\frac{PCU}{h} \right).$

Although this estimated capacity of movement using median U-turn is slightly lower than vehicles turn right directly from the major road (Bared & Kaisar, 2002) and the travel time is higher than direct right-turn traffic, the overall reduction in the travel time for the intersection is significant (Bared & Kaisar, 2002). An example of the network travel time benefit of the median U-turn may be found in Figure 2.10. The network travel time benefits rise rapidly after the entering flow of the intersection reaches 6000 vehicles.

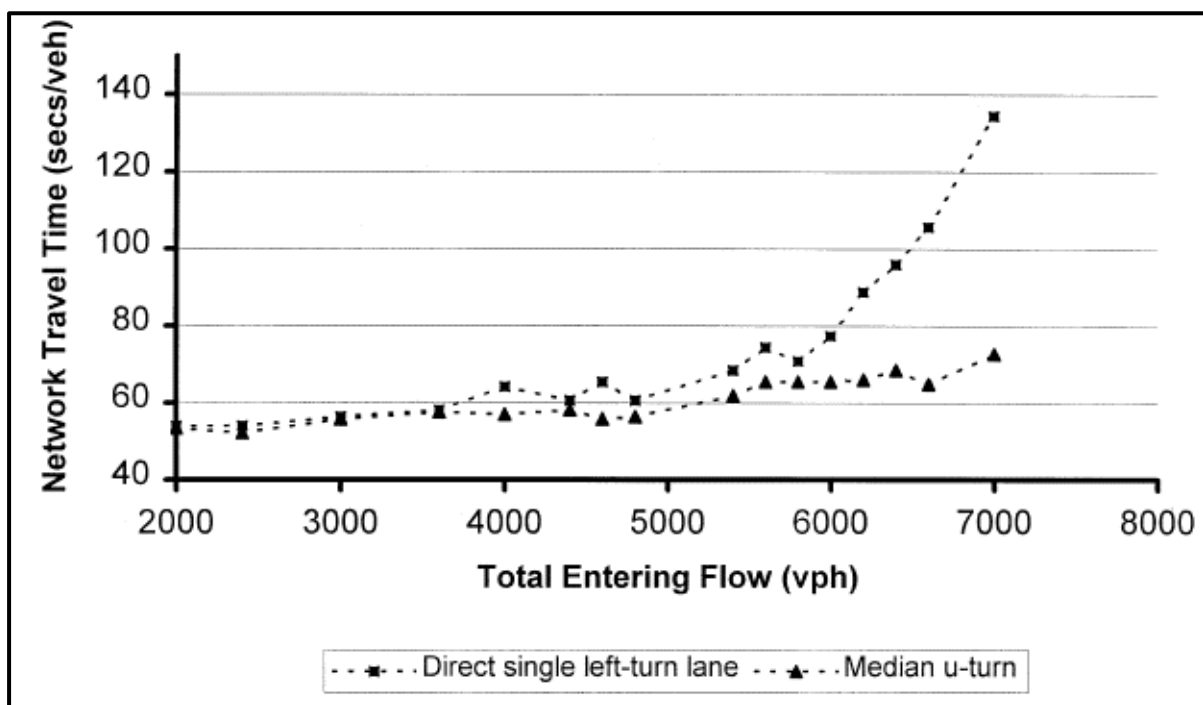


Figure 2.10 Network Travel Time Derived from Simulation at 10 Percent Right-Turn Volume (Bared & Kaisar, 2002)

Note: the word of “left” in this figure could be converted to the sides of “right” under a left-hand driving rule.

2.2.2.2 Superstreet

At an intersection within a superstreet network, movements of turning right onto the main street from the side streets are banned at the superstreet intersection (refer to

Figure 2.11). These drivers have to turn left first and then make a U-turn to come back to the intersection as part of the through vehicles.

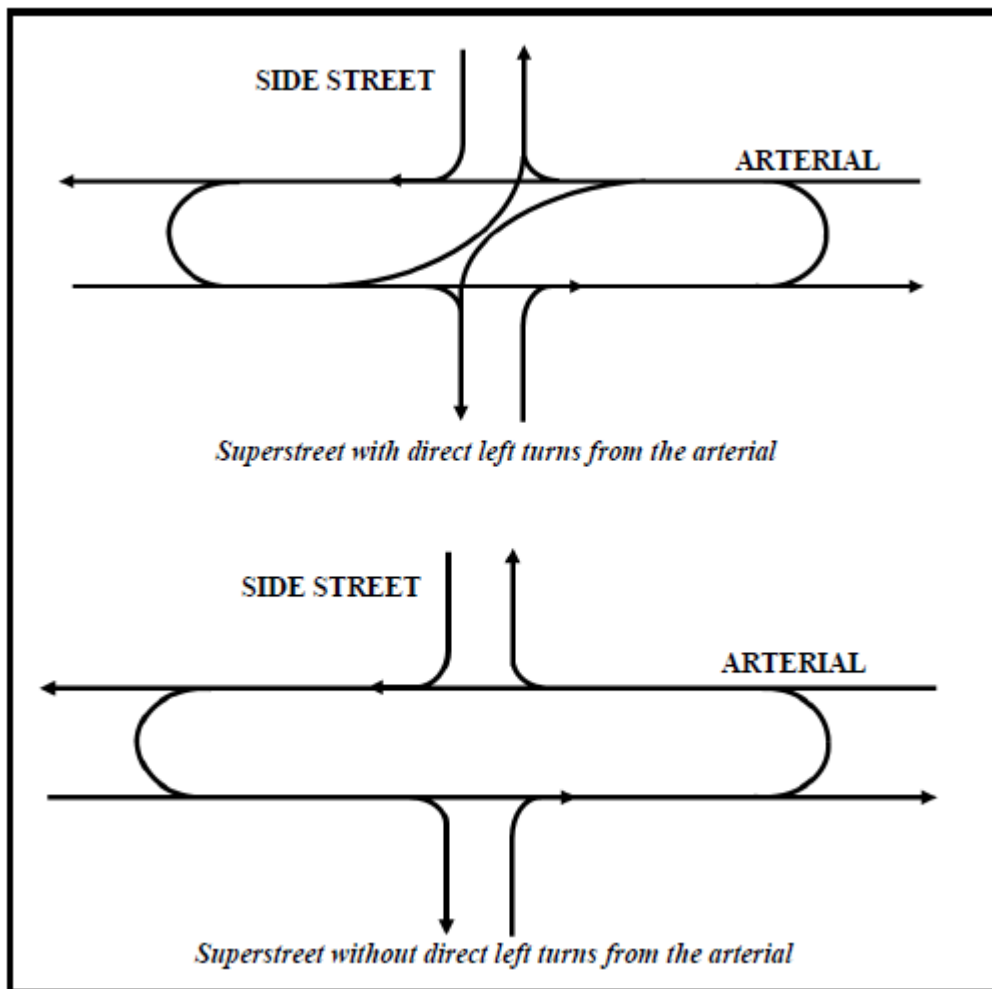


Figure 2.11 Layout of Intersections within Superstreet (Haley, 2010:2)

Note: the words and sides of "left" in this figure could be converted to the sides of "right" under a left-hand driving rule.

Intersections of the superstreet network were simulated using micro-simulation software VISSIM to study the travel time benefit of the superstreet network (Haley, 2010:3). Compared to the travel time consumed in the conventional intersections, the travel time for the traffic on minor roads was found to be increased. However, the travel time on the major road was reduced and the total travel time of the intersections within the superstreet network was reduced.

Additionally, signal time lost was reduced in the intersections in the superstreet network. It is because the right-turn stage and through stage of the minor roads were removed, which led to the relatively fewer number of signal stages in a signal cycle.

2.2.2.3 One-way network

Conflicts between right-turn movements and through movements are also reduced in a one-way network which is commonly applied in a downtown area because of its higher ability (compare to the conventional two-way network) of increasing vehicle flow (Gayah, 2012).

However, a two-way network with banned right turns has higher capacity and imposes less circuitry than a one-way network (Gayah, 2012).

2.2.3 Right-turn phasing operations

Generally, there are three modes of right-turn phasing operations, namely permissive, protected and protected/permissive.

2.2.3.1 Permissive (or permitted) mode

The turning movement is permitted but no exclusive turning phase is provided under this mode. It is the optimum option at small intersections with low traffic volume because of its fewer phases and shorter cycle length. It is not difficult for the right turners to find gaps in the oncoming through traffic and finish the right turn under light traffic conditions. Right turners can then pass through the intersection in a relatively short period with experiencing less delay.

However, as either of the right-turn volume or the oncoming through volume increases, the right turners would find it is difficult to find enough gaps to finish turning. If no separate right-turn bay/lane is provided or the right-turn bay is not long enough to store queuing vehicles, right-turning vehicles will block the through movement and significantly reduce the capacity of the approach. Some drivers may then lose patience and take risky actions, e.g., making right turn even when the gaps are not long enough to pass safely.

2.2.3.2 Protected mode

Vehicles are only allowed to turn right during a protected phase under this mode. It is considered as an effective way to solve the problems which a permissive mode faces. Right turners make the turning manoeuvre during an exclusive phase when they have the right-of-way and proceed without conflicting with other traffic. It

enables an intersection to have higher capacity and creates a safer environment to handle right-turn traffic. Many warrants for providing protected right-turn phases have been developed based on the following factors:

- Accident experience,
- Delay,
- Volumes,
- Traffic conflicts,
- Intersection Geometrics,
- Speed, and
- Other.

Agent and Deen (1978) developed very detailed warrants based on four criteria covering accidents, delay, volumes and conflicts.

2.2.3.2.1 Based on accidents

Accident data was collected from 24 intersections by conducting “before-and-after” tests to analyse the effect of the installation of the protected right-turn phases. It was found right-turn accidents dramatically dropped 85% while the total accidents only decreased 15%. And the “with and without” tests also showed accident rates of approaches with a protected phase were much lower than that of approaches without protected phases, while total accident rates of the target intersections were almost the same in both types of intersections.

Then based on the data of average number of right-turn accidents collected from the target approaches, a formula was developed (Agent & Deen, 1978) to determine the critical number of accidents as per Equation (3),

$$N_c = N_a + K\sqrt{N_a} + 0.5 \quad (3)$$

Where:

N_c = critical number of accidents,

N_a = average number of accidents, and

K = constant related to level of statistical significance selected

(for $P = 0.95$, $K = 1.645$; for $P = 0.995$, $K = 2.576$)

For $P = 0.995$, as per the formula, the critical number of right-turn accidents should be 4 per approach for 1 year and 6 per approach for 2 years.

2.2.3.2.2 Based on delay

When considering the practical and easy way to collect delay data, the stop delay in this study was defined as the time when the vehicle was actually stopped. The results showed that total intersection delay increased after installing protected right-turn phase regardless of whether it is a T-junction or a normal 4-leg intersection. While total right-turn delay also increased after the installation of protected phase at two locations, it was reduced during the periods of heavy traffic flow.

Because the major reason to install a protected right-turn phase is based on the excessive delay, warrants based on delay were developed using criteria of the mix of delay and volume. They were:

- Minimum right-turn volume during peak hour was 50 veh/hour/approach,
- Minimum average delay of right-turn traffic was 35 sec/veh, and
- The minimum total right-turn delay during peak hour was 2.0 vehicle*hours.

The total delay of vehicle*hours was calculated based on the following conservative conditions:

- Right-turn vehicles can only turn on amber because of no gaps available in the opposing traffic,
- Right-turn vehicles had to wait for almost the whole cycle because they arrive at the start of red phase, and
- 2 vehicles on average can finish turning during each amber phase.

2.2.3.2.3 Based on volume

In this study, delay was also considered when deriving the volume warrant because the data collected showed that volume alone cannot warrant the installation of the right-turn phase. Additionally, the number of the opposing lanes also makes a big difference on the volume product.

The volume warrants were derived based on the product of right-turn and opposing traffic volume during peak-hour conditions. Delays increased significantly after the

product reached the thresholds as shown below (the product curves are shown in Figure 2.12),

- Recommended threshold for two-lane street was 50000, and
- Recommended threshold for four-lane street was 100000.

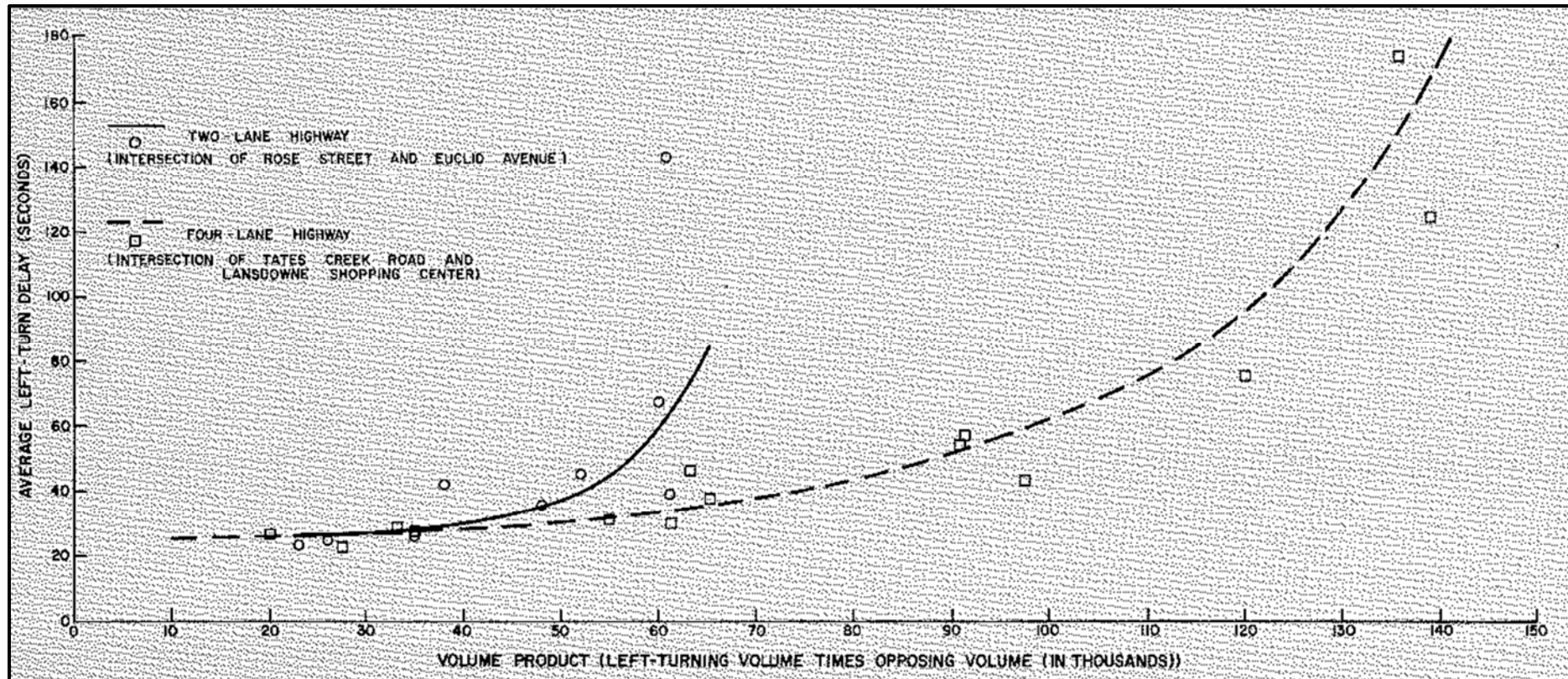


Figure 2.12 Relationship between Volume Product and Right-Turn Delay (Agent & Deen, 1978)

Note: the words "left" in the figure could be converted to the side of "right" under a left-hand driving rule.

2.2.3.2.4 Based on conflicts

The authors attempted to use the traffic conflicts technique to measure potential accidents rather than waiting for the accident to happen. Relationship between right-turn accidents and the average number of total right-turn conflicts were derived using the following linear regression model.

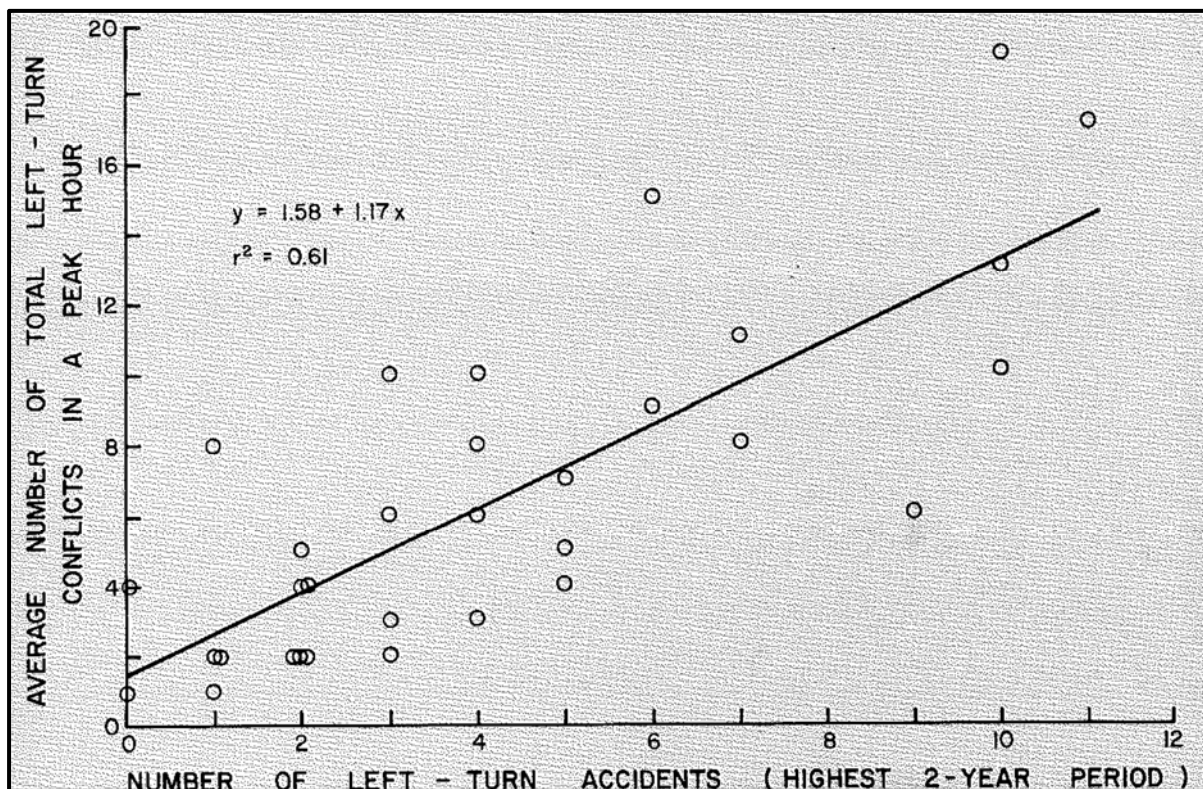


Figure 2.13 Right-Turn Accidents versus Total Right-Turn Conflicts (Agent & Deen, 1978)

Note: the words “left” in the figure could be converted to the side of “right” under a left-hand driving rule.

2.2.3.2.5 Other Warrants

Much research has been done on warrants for the protected right-turn mode based on different factors. Yu *et al.* (2008:31) summarised some of the warrants as shown in Table 7.1 and Table 7.2 (Appendix B).

2.2.3.3 Protected/permissive right-turn mode

In a protected/permissive right-turn mode, an exclusive protected right-turn phase is provided, whilst at the same time the right-turn movement is also permitted during the main phase. When compared to protected-only mode, protected/permissive

mode is considered to be more effective on handling right-turn traffic but not as safe as the protected-only mode for the drivers. This is partly because the protected/permissive phasing mode could potentially lead right-turn vehicles into a dangerous situation which is known as the “yellow trap”. The yellow trap happens during the moment when the through vehicles are having the yellow change interval. Right turners then enter the intersection because they thought the opposing through traffic is also going to be held by red, although it is still green for the opposing traffic.

Table 7.3 (Appendix B) presents a summary of warrants on selecting between the protected only mode and the protected and permissive mode (Yu *et al.*, 2008:31).

2.2.3.4 Summary

Actually, the choice between the 3 phasing operations above depends on which is more considered between efficiency and safety when making a decision. Therefore, in order to study the trade-off between efficiency and safety of different right-turn phasing modes, Shebeeb (1995) analysed the data of right-turn accidents in three consecutive years and the data of the average right-turn stopped delay per vehicle in the peak hour period from 54 intersections in Texas and Louisiana. Finally, the author plotted the relationships between right-turn accident rate and mean right-turn delay for different phase modes as shown in the Figure 2.14. The character “D” represents right-turn stopped delay and “A” represents the mean right-turn accident rate in the figure. As shown in the Figure 2.14, accident rates increased from the protected-only mode to protected/permissive mode and reached the highest pinnacle in the mode of permissive-only, while delay decreases in the same sequence between the 3 phasing modes. The author also suggested that the permissive right-turn phasing mode should always be preferable if priority was given to efficiency.

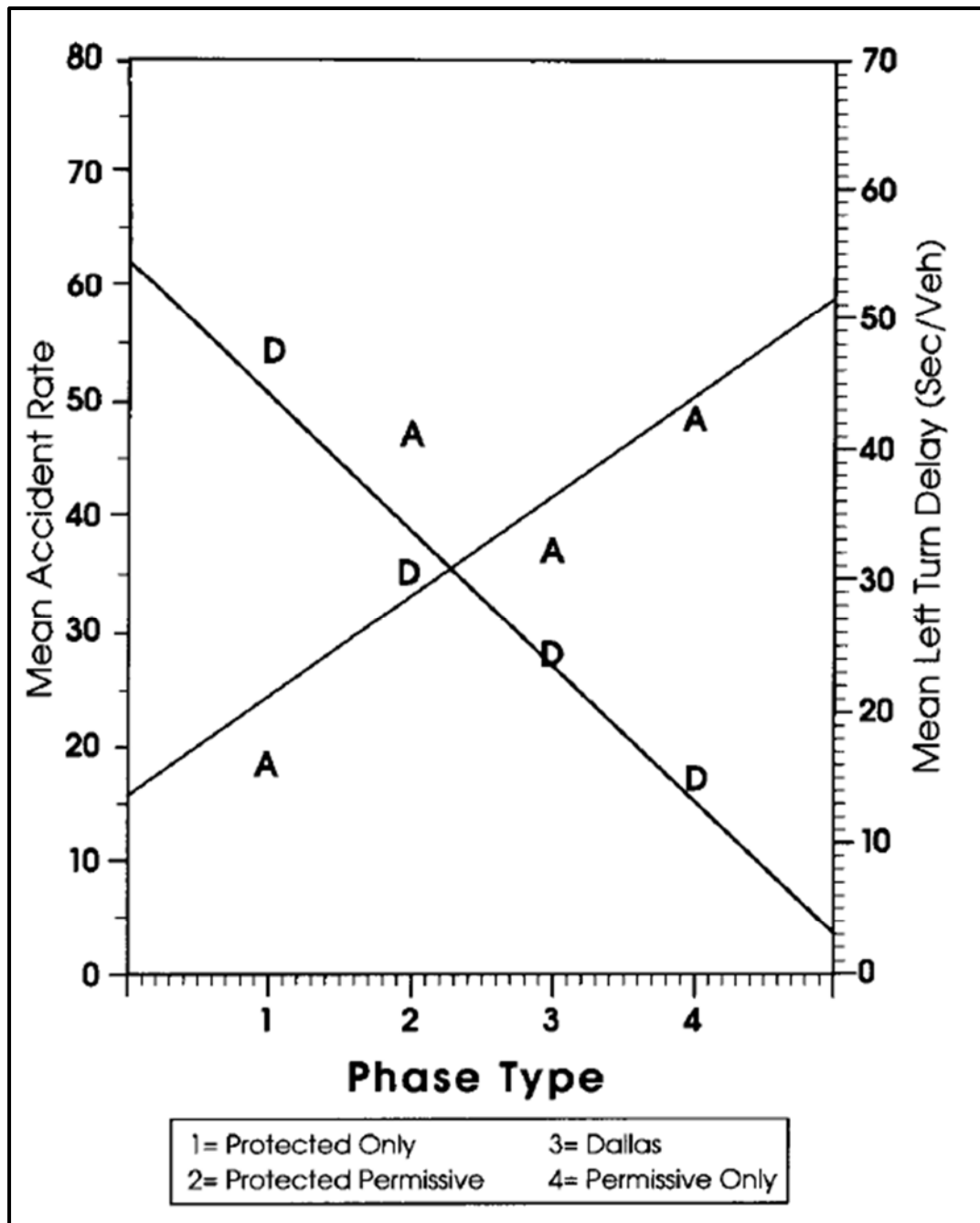


Figure 2.14 Trade-Off between Mean Right-Turn Accident Rate and Mean Right-Turn Delay for Each Phase Type (Shebeeb, 1995)

Note: the words "left" in the figure could be converted to the side of "right" under a left-hand driving rule.

2.2.4 Right-turn waiting zone

A right-turn waiting zone is a temporary storage place extending from the end of right-turn lane(s) at a stop line into an intersection. It is usually used together with a lagging right-turn phase (Yang, Liu, Tian & Wang, 2012). This design enables right-

turn vehicles to enter an intersection and wait in the waiting zone when the through signal of the same approach turns green. When the right-turn phase starts turning green after the through phase, vehicles in the waiting zone could clear the intersection early. Figure 2.15 presents a typical layout of a signalized intersection designed with waiting zones.

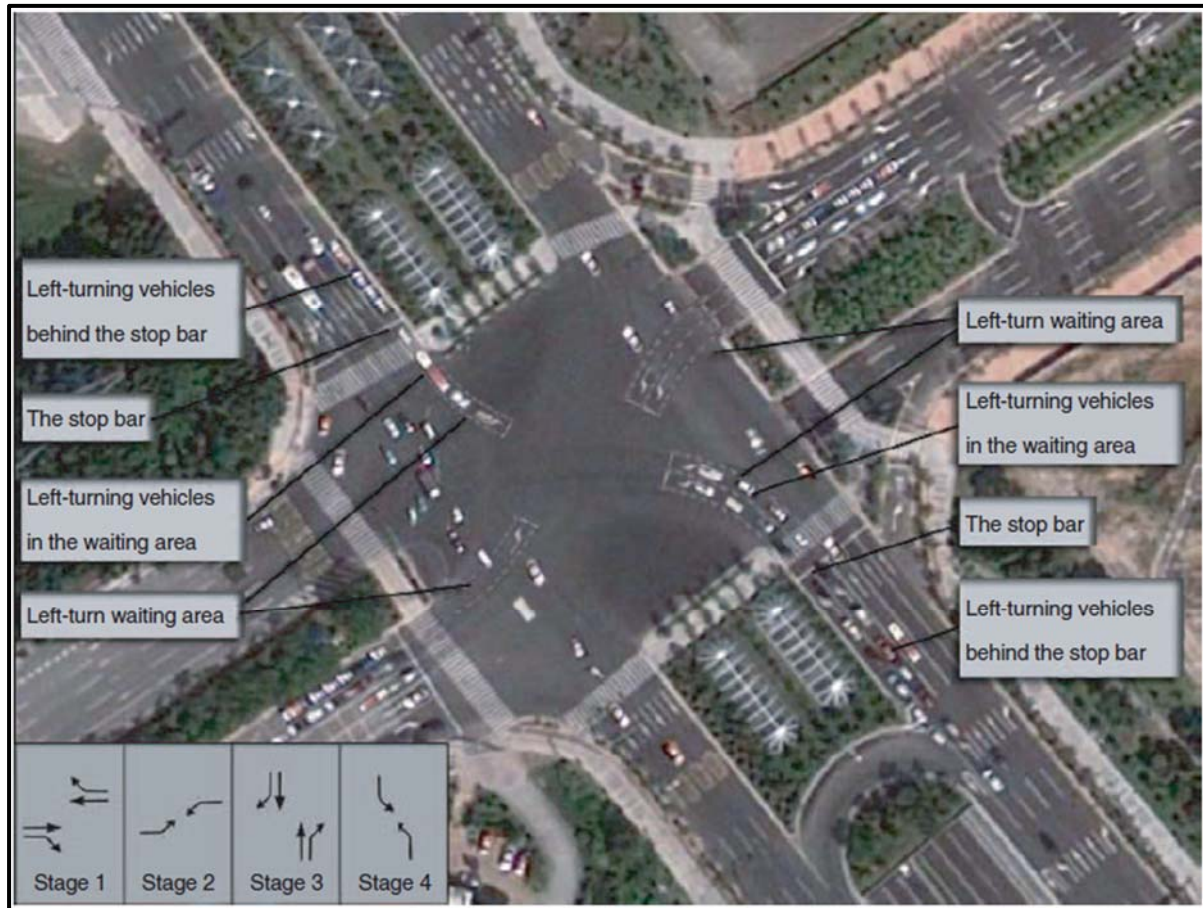


Figure 2.15 Typical Layout of Signalized Intersection with Right-Turn Waiting Zone (Yang *et al.*, 2012)

Note: the words and sides of “left” in this figure could be converted to the sides of “right” under a left-hand driving rule.

A research (Yang *et al.*, 2012) showed that the right-turn waiting zones could increase the capacity of the right-turn movement at an approach with separate right-turn lane(s). The authors compared the capacity benefits between different sizes of right-turn waiting zones and found benefit capacity increases as the size of the waiting zone increases.

The effects of a right-turn waiting zone on some characteristics of the right-turn traffic flow were also studied. Both the saturation flow rates of the right-turn traffic with or

without a right-turn waiting zone were found not significantly different, i.e., 2.14 seconds and 2.10 seconds respectively.

However, the installation of right-turn waiting zones could increase the start-up lost time. Based on the data collected, average start-up lost time for vehicles after the stop line with or without right-turn waiting zones were found to be 5 seconds and 3.44 seconds respectively.

2.2.5 Continuous Flow Intersection

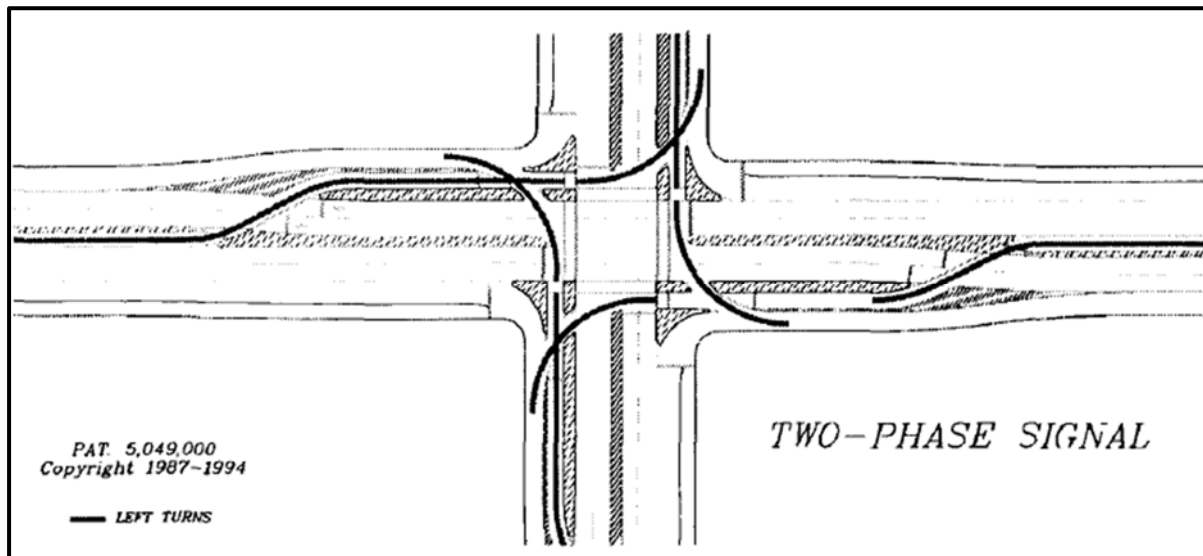


Figure 2.16 A Typical Layout of a Continuous Flow Intersection (Goldblatt, Mier & Friedman, 1994)

Note: the words and sides of “left” in this figure could be converted to the sides of “right” under a left-hand driving rule.

A continuous flow intersection (Mier & Romo, 1991) is an alternative design to deal with right-turn movement at at-grade intersections. Figure 2.16 presents a typical layout of a continuous flow intersection designed on four approaches.

As an at-grade solution, a continuous flow intersection removes the conflicts between the right-turn traffic and the opposing traffic to improve capacity by displacing a stretch of the right-turn lane ahead of the intersection to the right of the opposing traffic. Additionally, the reduction of phases per signal cycle saves the time which is lost while switching signal phases. Performance such as delay, speed, fuel consumption and vehicle emissions of the conventional and continuous flow intersections were simulated and compared. A continuous flow intersection was

found offering significant advantages over a conventional intersection (Goldblatt *et al*, 1994). The number of vehicles served in the two types of intersection is compared in Figure 2.17.

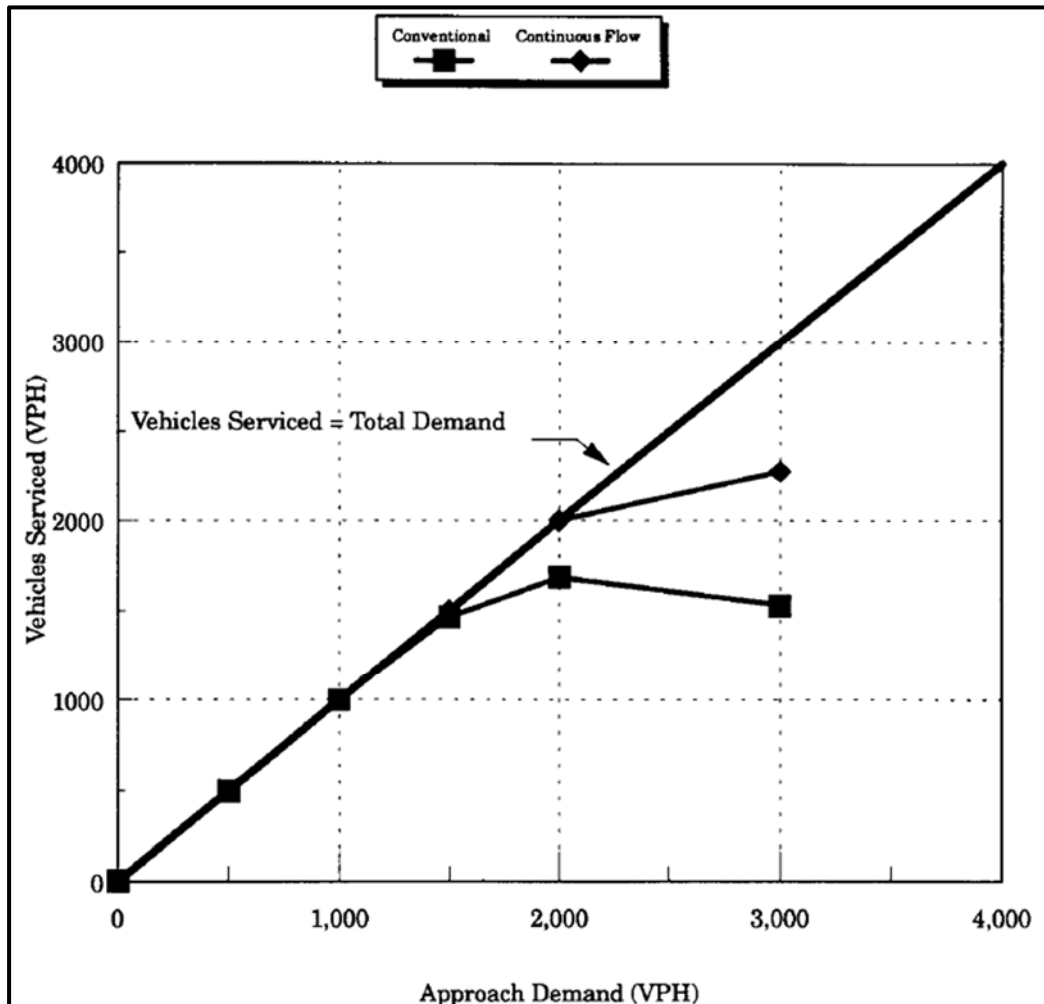


Figure 2.17 Comparison of Conventional and Continuous Flow Intersection: Vehicles Served (Goldblatt *et al*, 1994)

Despite the advantages, this tactic causes confusion among the drivers during the first few years after its installation and it takes time to get the drivers familiarised with the continuous flow intersection (Park & Rakha, 2010). Additional research comparing pedestrian performance between the CFIs and the conventional intersection still need to be done (Jagannathan & Bared, 2005).

2.2.6 Diverging Diamond Interchange

When an arterial crosses over/under a freeway, normally it creates a diamond interchange with two intersections located on both sides of the freeway. It is possible

that either the right-turn vehicles or the through vehicles from the arterial may conflict at these two intersections. A typical diamond interchange is shown in Figure 2.18. An example of the traffic flow organization in a DDI may be denoted by in Figure 2.19.



Figure 2.18 Typical Diamond Interchange (N1/M16 in Cape Town, South Africa. Google Maps)

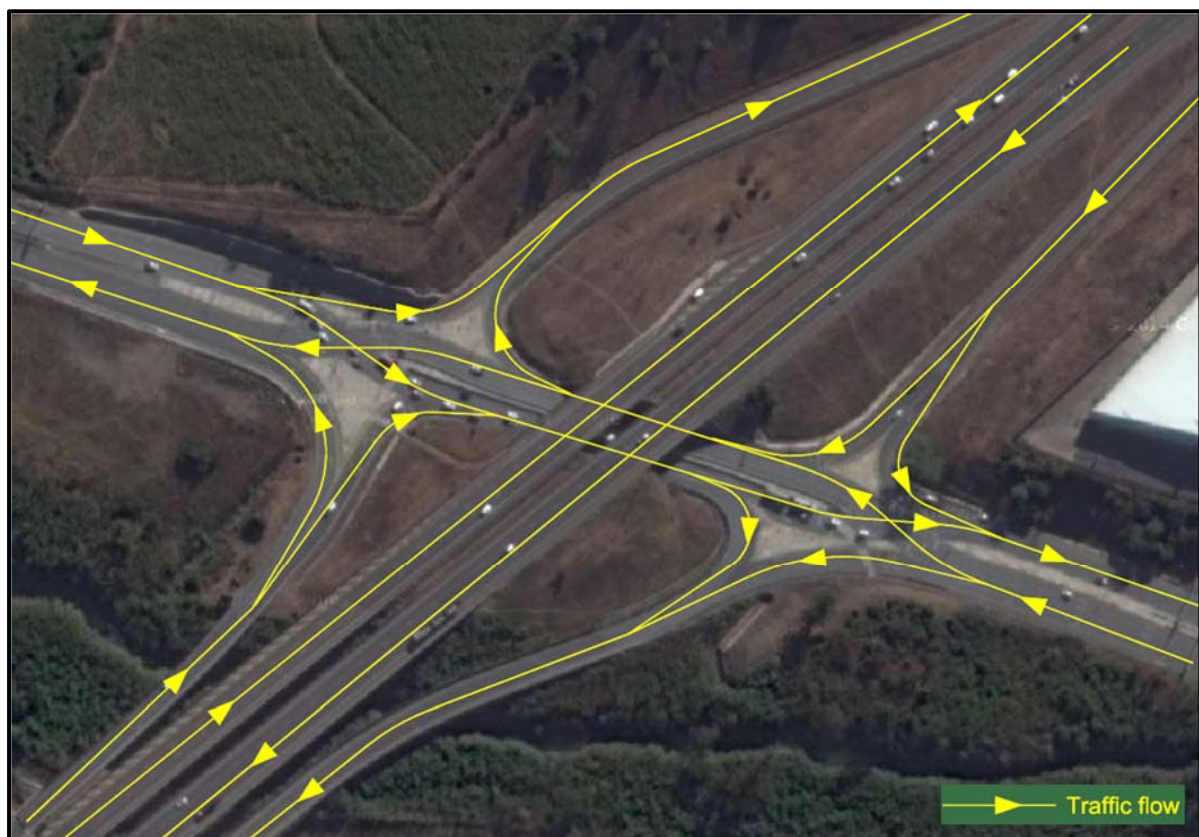


Figure 2.19 Traffic Flow Organization in Diverging Diamond Interchange (N2/Curnick Ndlovu, Durban, South Africa. Google Maps)

When compared to the conventionally designed diamond interchange, diverging diamond interchange (DDI) eliminates a phase in the signal cycle. Once vehicles pass the first intersections of the two, right-turn vehicles can turn onto ramps without experiencing the conflict points of the next intersection. In other words, exclusive right-turn signals are removed. The DDI has a higher ability to handle right-turn vehicles (capacity could be doubled) with lower delays, fewer stops, lower stop time and shorter queue lengths under higher traffic volume condition (Bared, Edara & Jagannathan, 2005).

2.3 Pre-signal strategy in transit system

Bus pre-signal control, like many other bus priority methods used in Transit Signal Priority in urban areas, gives priorities to buses to improve the services, thus to attract more travellers using public transport. Figure 2.20 & Figure 2.21 present two different configurations of approaches designed with pre-signals, denoted as category A and B respectively. Based on category B, detectors could also be added to the bus lane to reduce delay caused by the pre-signals.

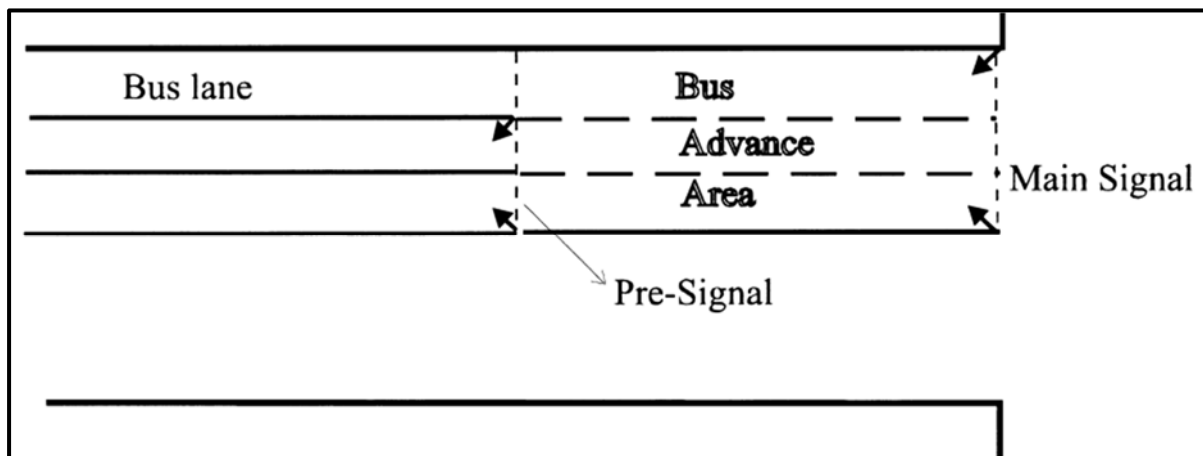


Figure 2.20 Configuration of Approach Implied With Pre-Signal Category A (Wu, 1998)

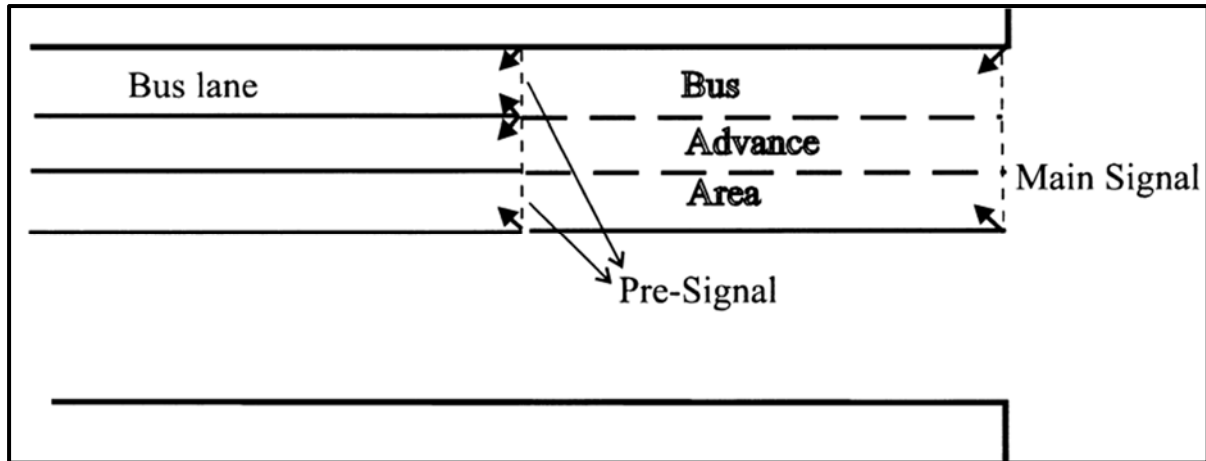


Figure 2.21 Configuration of Approach Implied With Pre-Signal Category B (Wu, 1998)

This strategy was first implemented in Europe and was first documented in a report in the Department of Transport in U.K. in 1991. Then a significant number of pre-signals were implemented in the U.K. after the first trial in Shepherd's Bush in London in 1993 (Wu, 1998).

In an effort to evaluate the pre-signal strategies, Wu (1998) chose delay as an index to compare both approaches with and without pre-signal installation. Total bus delay per cycle at the main signal is equal to:

- $\frac{r_m}{2}$ in Figure 2.22 for approach without pre-signal,
- The area of ABEF and part of the BCDE in Figure 2.23 for approach with pre-signal category A, and
- The area of AJBEK in Figure 2.24 for approach with pre-signal category B.

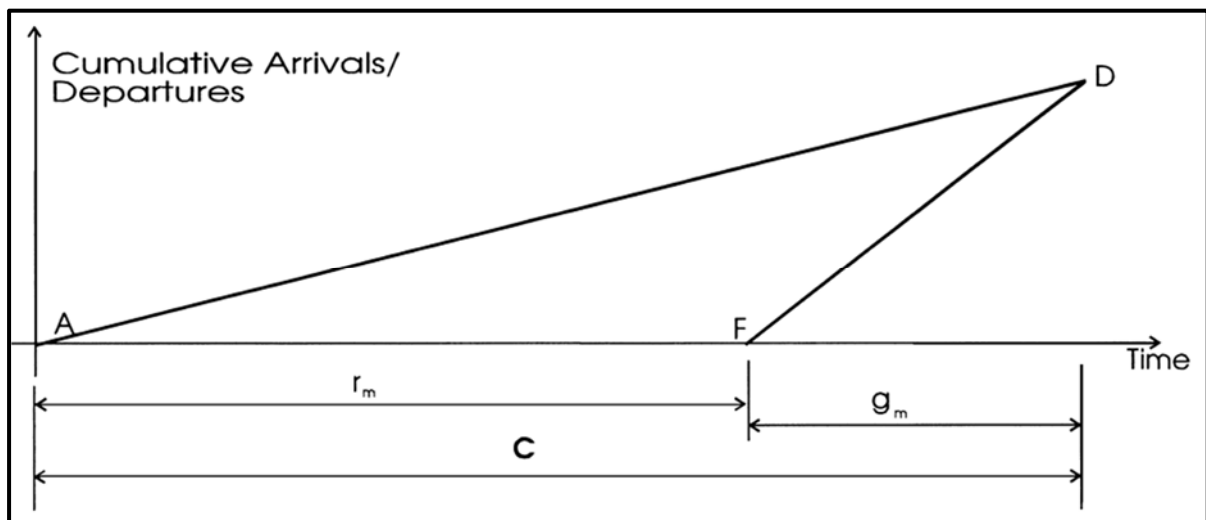


Figure 2.22 Arrivals and Departures in Approaches without Pre-Signal (Wu, 1998)

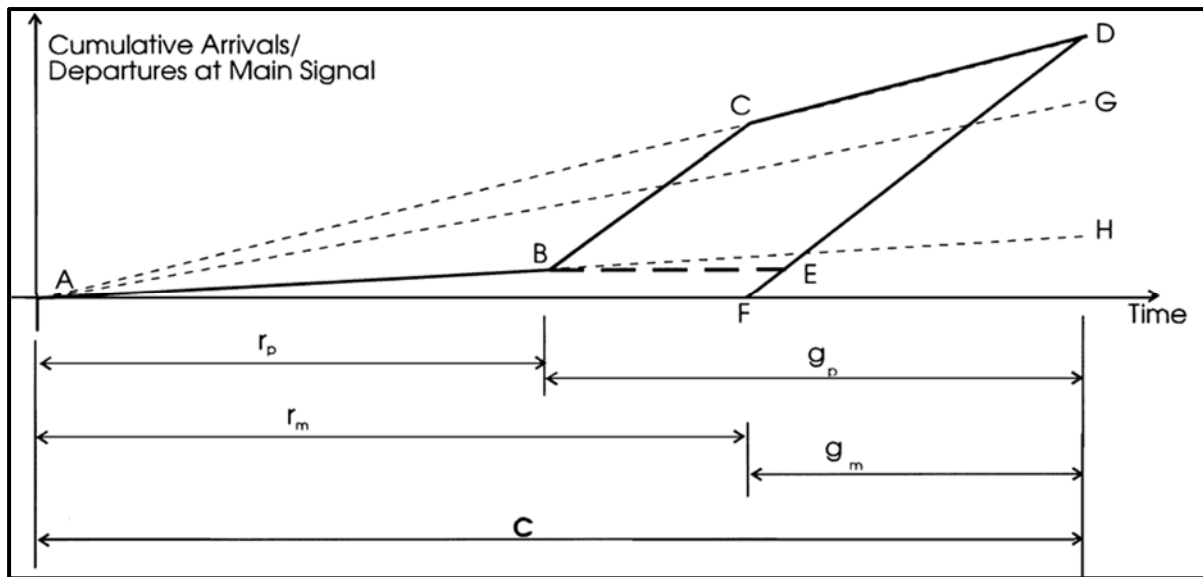


Figure 2.23 Arrivals and Departures in Approaches with Pre-Signal Category A (Wu, 1998)

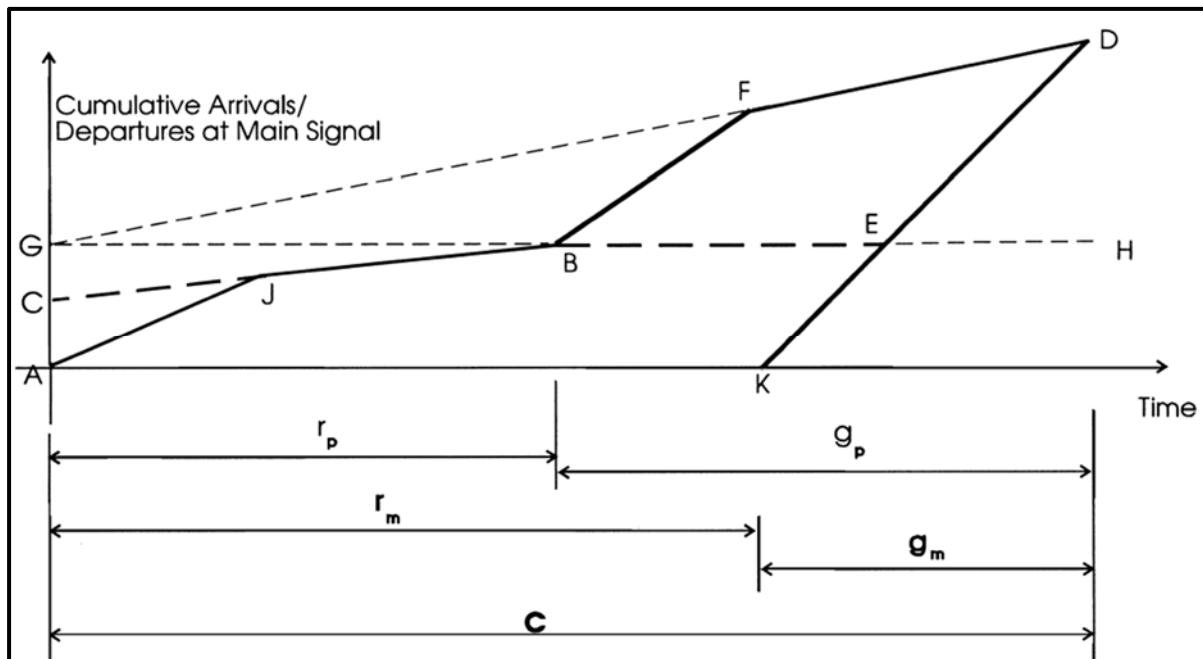


Figure 2.24 Arrivals and Departures at Main Signal with Pre-Signal Category B (Wu, 1998)

In effect, the author made conclusions that pre-signal category A could reduce bus delay without significantly affecting non-priority vehicles, while category B failed to improve bus delay.

It should be noted that this study was based on two ideal assumptions:

- Space of the area between main signal and pre-signal will be fully used by the co-ordination of the two signals, which means the area should be filled up with

non-priority vehicles (vehicles except buses) before the main signal turns green.

- The area between the two signals should be cleared at the end of the main green.

2.4 Pre-signal theories for general traffic

2.4.1 Introduction

A pre-signal strategy has been used in transit systems for more than 20 years. It was also found applicable to general traffic (i.e., mixed vehicle types in traffic flow) at signalized intersections recently. Although there are different types of pre-signal concepts, e.g., tandem concept (Xuan *et al.*, 2011:769-781) and phase swap concept (Xuan, 2011), the main value of the pre-signal concept is to increase the capacity of an approach by providing more lanes in the sorting area to discharge vehicles during their green time.

2.4.2 Former research

The earliest idea of developing the pre-signal theory as a general traffic control method could be found as a patent registered by Wang (1999). Wang developed an idea of using pre-signal to create a sorting area where through vehicles and turning vehicles could enter by an in turn and subsequently, vehicles could be discharged by using all the lanes of the approach, thus to increase capacity.

Xuan *et al.* (2011:769-781) developed a pre-signal concept named the tandem intersection concept. In this concept, a pre-signal with a pre-stop line was applied upstream of an approach to form a sorting area between the pre-stop line and the main stop line. After being reorganized by the pre-signal, through vehicles and right-turn vehicles enter in the sorting area in turn to form a tandem traffic flow. Vehicles then can occupy part of or all lanes of the approach and wait to be discharged from the main stop line (left-turn vehicles can also participate the sorting if necessary). Figure 2.25 presents how the traffic movements were re-organized in the sorting area.

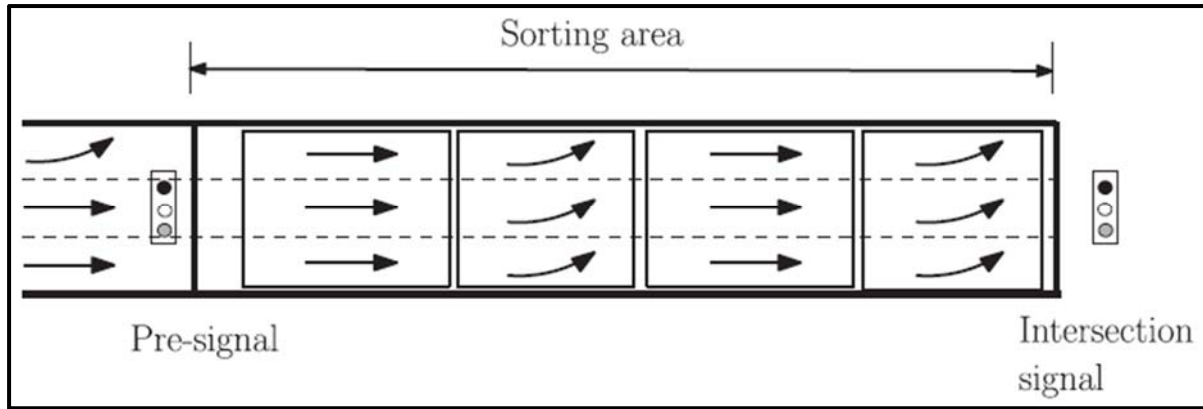


Figure 2.25 Tandem Intersection Concept (Yan *et al.*, 2013)

Note: the left-turn movement in this figure could be converted to right-turn movement under a left-hand driving rule.

Comparisons on capacity were done between the conventional approach and the tandem approach. It was found approaches applied with the tandem pre-signal strategy had a significantly higher capacity under conditions of properly timed signals and with a proper percentage of turning volume. One of the comparisons is shown in Figure 2.25.

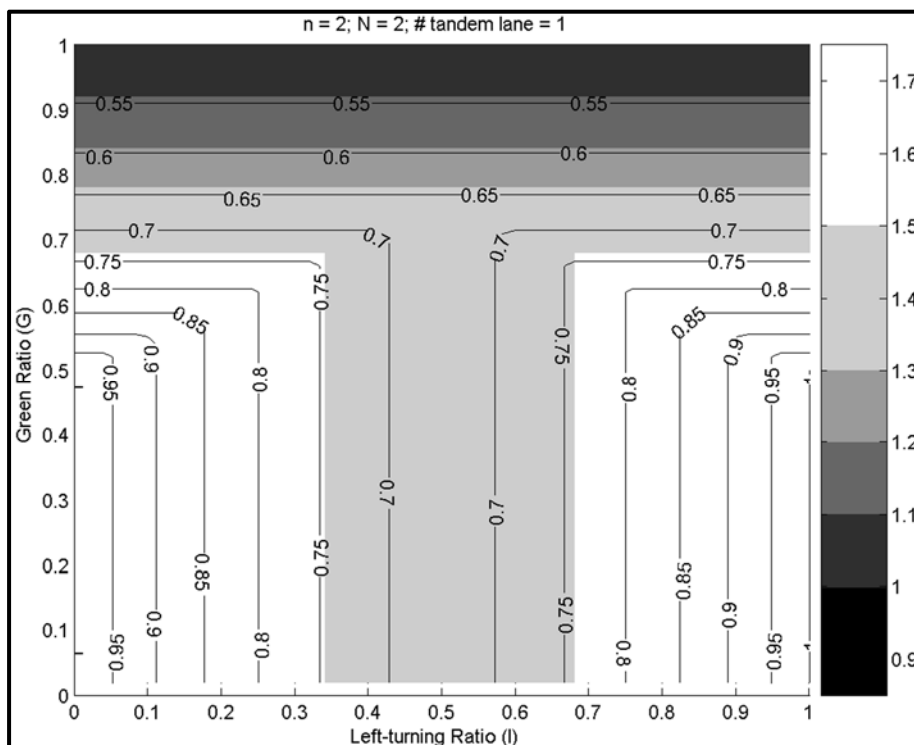


Figure 2.26 The Ratio of Tandem Capacity over Congenital Capacity (Xuan *et al.*, 2011)

Note: the word of "left" in this figure could be converted to the word of "right" under a left-hand driving rule.

However, intersections with low traffic volumes would not benefit from the tandem concept. This concept should only be applied under conditions of high traffic volumes or during the peak hour period. Another disadvantage of the tandem pre-signal designed approach is that the sorting area consumes a long stretch of the street, which may limit the application of the concept in reality where the spacing between two intersections is short.

Later, Xuan (2011) succeeded in reducing the length of the sorting area by swapping the phases to allow only through vehicles or right-turn vehicles to queue in the sorting area at a time. The phasing option may be found by referring to Figure 2.27.

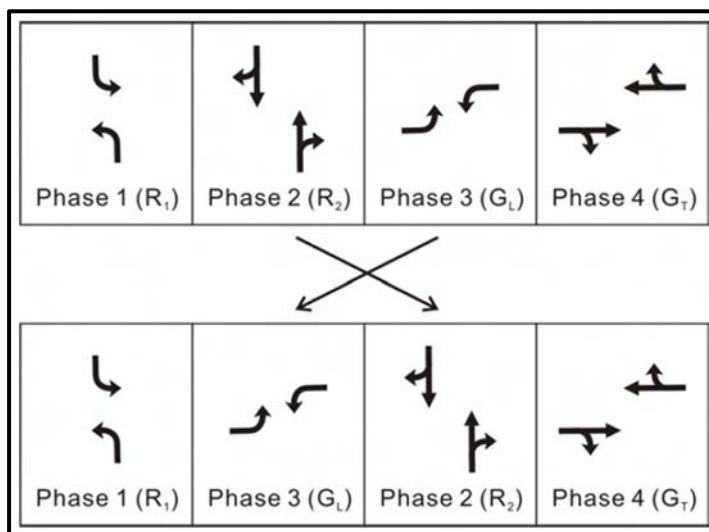


Figure 2.27 Phase swapping Option (Xuan, 2011)

Note: the left arrow in this figure could be converted to right arrow under a left-hand driving rule.

2.5 Signal coordination

Coordination is a tool to provide “the ability to synchronize multiple intersections to enhance the operation of one or more directional movements in a system” (Koonce, Rodegerdts, Lee, Quayle & Beird, 2008:6-1). Although signal coordination is mostly used between numbers of intersections, the pre-signal controlled approach of a signalized intersection also needs to be coordinated.

In a pre-signal designed approach of a signalised intersection, the approach can only reach its capacity when the sorting area is fully occupied by waiting vehicles. The pre-signal is a “feeder” which controls the access of vehicles coming into the sorting area. If not coordinated well, drivers could be held at the pre-signal and green time at

the main signal may be wasted. Therefore, the coordination between the pre-signal and main signal is a decisive factor that affects the capacity of an approach.

2.5.1 Cycle length

The prerequisite of coordinating signals is that signals must have the same cycle length. This is the critical requirement to ensure a smooth traffic flow with less signal hindrance.

2.5.2 Time-space diagram and offset

2.5.2.1 Time-space diagram

The time-space diagram is used to plot the relationships between the coordinated signals as a function of time. Distance between the signals is usually set as the scale of the time-space diagram. Figure 2.28 presents a simple example of a time-space diagram for two coordinated intersections.

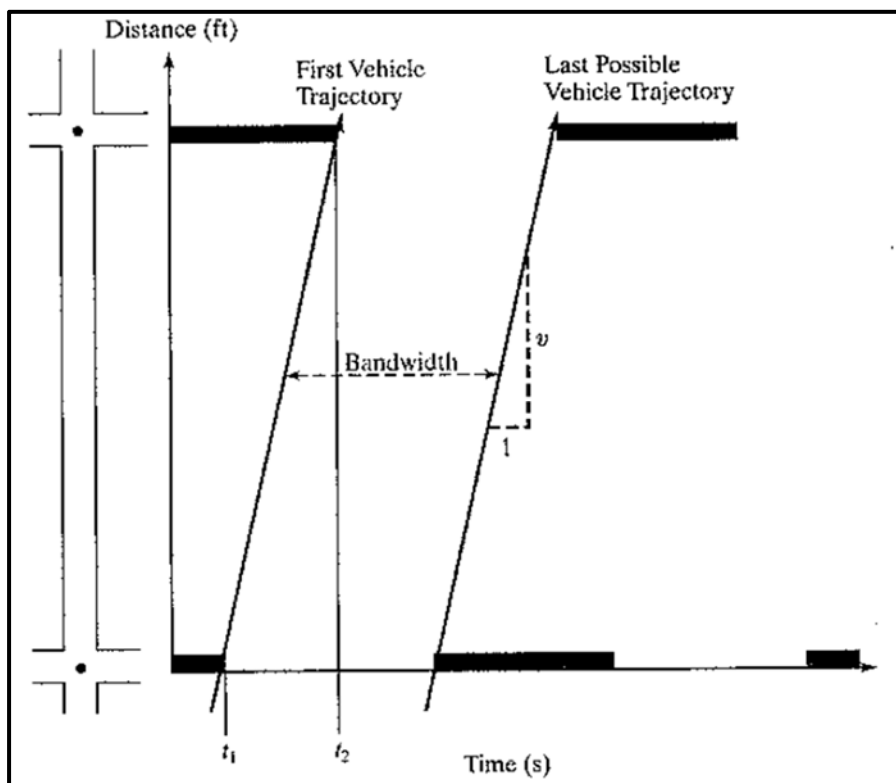


Figure 2.28 Time-Space Diagram (Roess, 2004:685)

2.5.2.2 Offset

The signal offset refers to the interval of the green initiation times, while the ideal offset means the offset with which the first vehicle of the platoon always arrives at the downstream signals at the time they turn green.

The offset in the example shown in Figure 2.28 is an ideal offset. It is equal to t_2 minus t_1 , or can be calculated by (Roess, 2004:685),

$$t_{ideal} = L/S \quad (4)$$

Where:

$$t_{ideal} = \text{ideal offset, (s)}$$

$$L = \text{distance between signalized intersections, (m)}$$

$$S = \text{average speed, } \left(\frac{m}{s}\right)$$

2.5.3 Coordination under oversaturated conditions

While minimizing delay and stops are the top objectives for an under-saturated intersection, it shifts to the following objectives (Roess, 2004:704) for an oversaturated intersection:

- 1) Maximizing system throughput by a) avoiding queue spills back and blocks intersections upstream; (b) avoiding starvation which wastes green time; (c) managing queue to serve as much vehicles crossing the stop line as possible.
- 2) Fully utilising storage capacity by storing vehicles in a limited area under a “feed forward” system.
- 3) Provide equitable service by balancing the right-of-way allocated to through and turning traffic.

The objectives of applying signal coordination in a pre-signal system are in accordance with the objectives listed above because pre-signal is designed for approaches under heavy traffic conditions, although oversaturation is not required.

2.6 Important elements in signal timing

Figure 2.29 presents a basic view of a flow rate when queuing vehicles move through a stop line of a signalized intersection.

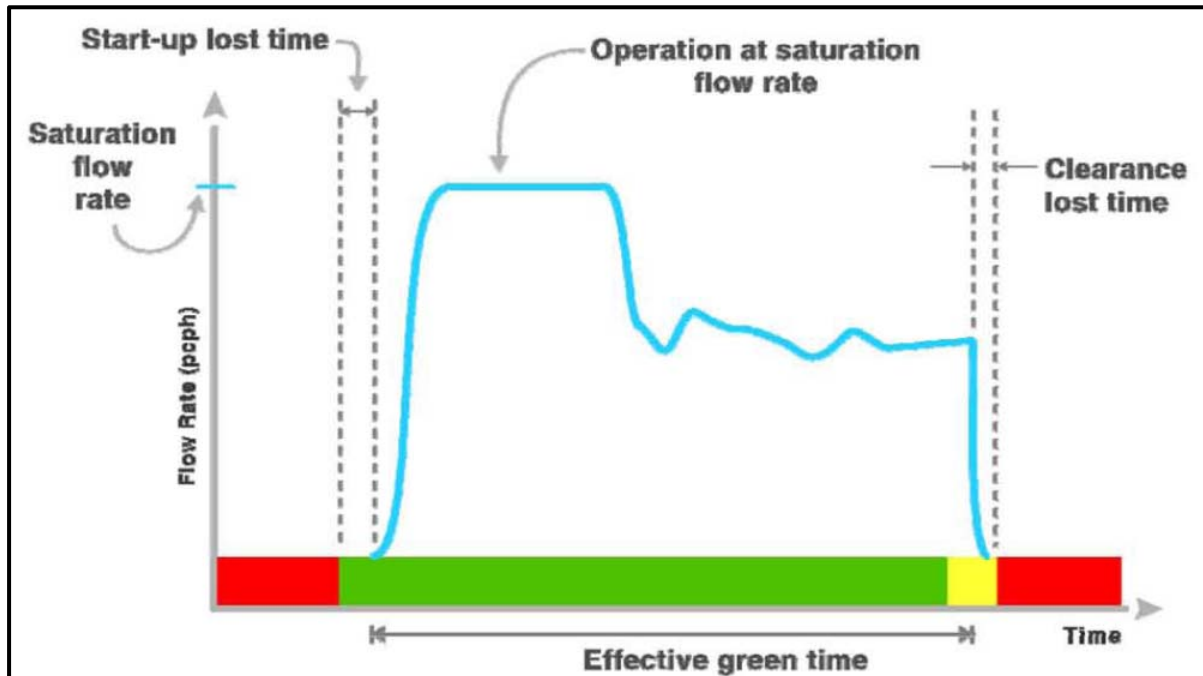


Figure 2.29 Typical Flow Rates at a Signalized Movement (Koonce, 2008:3-6)

As shown in the figure, the flow rates vary from period to period of the signal. Some of the important periods of a signal cycle are reviewed below.

2.6.1 Start-up lost time

As explained in HCM 2010 (TRB, 2010:4-11), start-up lost time, when compared to a saturation flow, is the extra time that the first few vehicles of the stopped platoon consumes when they pass the stop line. In this theory, it is assumed that the first four vehicles are affected with the start-up time lost while the successive vehicles cross the stop line at saturation headways. The headway of the first vehicle, defined as the time elapsed between the initiation of green and the moment the front/rear wheel/bumper of the first vehicle reaches the stop line, is usually the highest. The headway decreases as the vehicles of the queue pass the stop line and the lost time dissipates after the first few vehicles passed the stop line. This assumption is clearly shown in Figure 2.30 & Figure 2.31.

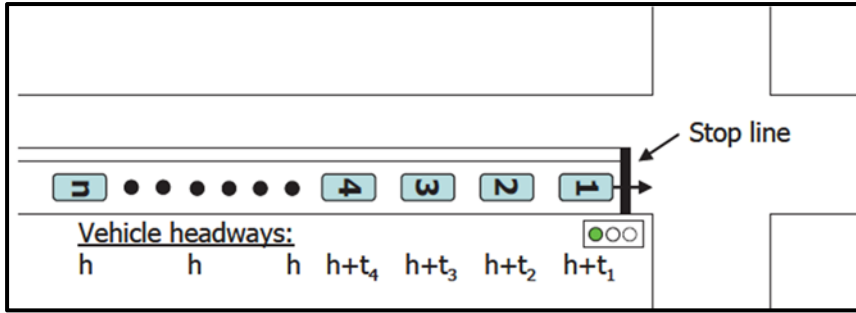


Figure 2.30 Headways at a Signalised Intersection (TRB, 2010:4-11)

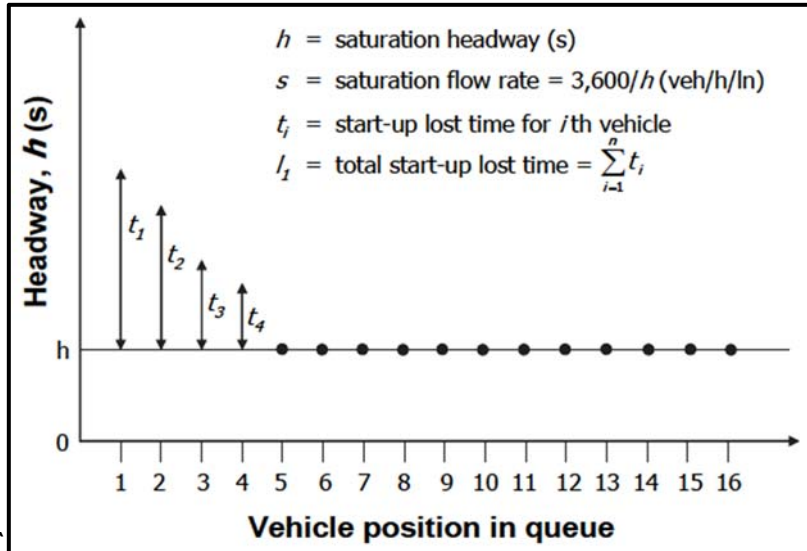


Figure 2.31 Concept of Saturation Flow Rate and Lost Time (TRB, 2010:4-12)

The total start-up lost time is calculated by (TRB, 2010:4-12):

$$l_1 = \sum_{i=1}^n t_i \quad (5)$$

Where:

l_1 = total start – up lost time (s),

t_i = lost time for i^{th} vehicle in queue (s), and

n = last vehicle in queue.

Much research has been conducted on studying the total start-up lost time based on the assumption explained above. Some researchers (Bester & Varndell, 2002) also paid attention to the impact of a leading right-turn green phase on the start-up lost time. The value of l_1 was found to be,

- Approximately 2 seconds in Traffic Signal Timing Manual (2008:3-5).

- Ranging from 0.75 to 3.04 seconds without considering leading green phase.

Table 2.1 Start-Up Lost Time without Considering Leading Green Phase (Bester & Varndell, 2002)

Source	Date	Location	Start-up lost time (s)
Gerlough	1967	Los Angeles	2.05
Carstens	1971	Ames, Iowa	0.75
King	1976	USA	-
Agent	1983	Lexington	1.40
Lee	1986	Kansas	3.04
Molina	1986	Texas	-
Zegeer	1986	Various	1.31
Fambro	1987	Houston	-
Roess	1988	Various	-
Short	1989	Texas	1.31
Gaston	1991	Dallas	-
Zegeer	1992	Florida	-
Jacobs	1998	Stellenbosch	1.43

Table 2.2 Start-Up Lost Time Considering Leading Green Phase (s) (Bester & Varndell, 2002)

	Opposing Traffic	Subject Traffic
Dorp/Strand Street Intersection	3.2	2.1
Van Reede/Strand Street Intersection	2.7	2.2

2.6.2 Saturation headway

The saturation headway, denoted as h , is estimated as the average headway between the rest of the vehicles in platoon except the first four. Saturation flow rate can be derived by the saturation headway as follows:

$$q = \frac{3600}{h_s} \quad (6)$$

Where:

q = saturation flow rate (veh/h), and

h_s = saturation headway (s).

HCM 2000 (TRB, 2000) suggested a base saturated headway of 1.895s and saturation headway of 2.0s for protected left turns.

Research had also been done in Stellenbosch, South Africa to study the local saturation flow rate. The results are shown below.

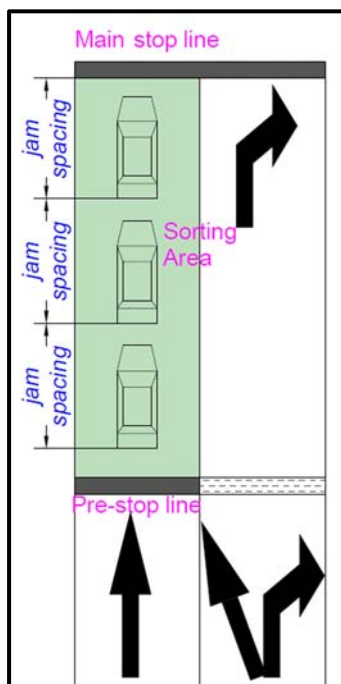
Table 2.3 Saturation Flow Rates (Bester & Meyers, 2007)

Intersections	Saturation flow rate (veh/h/lane)
Dorp/Strand	2026
Molteno/Bird	1711
Adam Tas/Bird	1820
Strand/ Van Reede (-G)	2197
Strand/ Van Reede (+G)	2044
Paarl/Welgevonden	2000
Webersvallei/R44 (-G)	2370
Webersvallei/R44 (+G)	2076
Strand/Van Reede (Right)	1840
Strand/Saffraan (Right)	1920

It was found in the study that the saturation flow rate was higher in South Africa than in other countries and a right-turn lane with exclusive phase could have a higher saturation flow rate than that of a through lane.

2.6.3 Jam spacing

As defined in the HCM 2010 (TRB, 2010:4-7), spacing is “the distance between successive vehicles in a traffic stream, measured from the same point on each vehicle (e.g., front bumper, front axle)”. While jam spacing (Figure 2.32), on the other hand, is the spacing for the vehicle in a stationary queue. It equals the sum of gap (space) length and vehicle length.

**Figure 2.32 Jam Spacing**

A study (Akçelik and Besley 99-118) conducted in Australia has shown that the average jam spacing collected from stationary queues before stop lines ranged from 5.9m to 7.3m (heavy vehicles were excluded).

2.6.4 Clearance lost time

Clearance lost time, denoted as l_2 , is defined by HCM 2010 (TRB, 2010:4-13) as the time interval when no traffic movements proceed into the intersection.

The time interval is designed to provide a safe environment when the signal switches right-of-way between conflicting movements. In practice, it is usually presented as a combination of yellow and red clearance interval, which can be calculated by (TRB, 2010:4-13):

$$l_2 = \gamma + R_c - e \quad (7)$$

Where,

γ = yellow change interval (s),

R_c = red clearance interval (s), and

e = extension of effective green (s).

2.6.5 Effective green time

Effective green time is defined by the Traffic Signal Timing Manual (Koonce *et al.*, 2008:6-1) as: “the time during which a given traffic movement or set of movements may proceed; it is equal to the cycle length minus the effective red”. It is the time duration from the end of the start-up lost time to the end of the yellow extension. It can be derived from the following formula (Koonce *et al.*, 2008:3-7),

$$E = G + \gamma + R_c - (l_1 + l_2) \quad (8)$$

Where,

E = effective green, (s)

G = green time of the phase. (s)

Substituting Equation(7) into the Equation(8), it gives

$$E = G + e - l_1 \quad (9)$$

2.7 Lane change

In the pre-signal concept, movements that use sorting areas benefit from the extra discharging lane(s). This forces some of the drivers to make lane changes to enter the sorting area.

Lane change could be divided into three parts (Olsen, 2003:13). It is the time and distance needed for a vehicle to 1) move from a straight-ahead position in the original lane and intercept the lane line, 2) completely cross that line, and 3) return to a straight-ahead position in the destination lane.

A typical lane change trajectory (Yao, Zhao, Davoine & Zha, 2012:885-890) is shown in Figure 2.33. The longitudinal and lateral distances used to finish a lane change covering two lanes are $|y_1 - y_0|$ and $|x_1 - x_0|$.

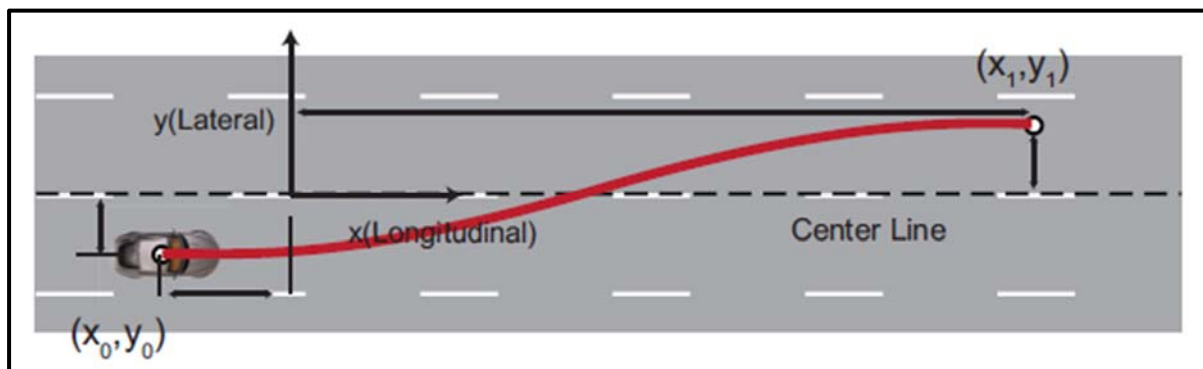


Figure 2.33 A Typical Lane Change Trajectory Covering Two Lanes (Yao *et al.*, 2012:885-890)

2.8 Summary

Literatures about the following items were reviewed in this chapter:

- Warrants for providing right-turn lanes/bays and the design of right-turn lanes/bays;
- Three right-turn phasing options, including permissive, protected and permissive/protected. Trade-offs between permissive and protected phasing options;
- Alternative designs of signalized intersections, including right-turn waiting zone, continuous flow intersection and diverging diamond intersection;

- Pre-signal theories for both transit system and for general traffic;
- Signal coordination;
- Important elements in signal timing, including start-up lost time, saturation flow, jam spacing, clearance lost time and effective green time; and
- Lane change manoeuvres,

CHAPTER 3 METHODOLOGY

3.1 Introduction

This chapter introduces the basic assumptions of the study and the methods used to establish the relationships between the capacity and some important factors of an approach in an at-grade intersection with a separate right-turn phase. The signal time utilization and sorting area space utilization are considered because these two factors in reality will reduce the benefit estimated under theoretical studies.

3.2 Methodology

3.2.1 Basic assumptions

With the purpose to simplify this research and concentrate on the main problems, some basic assumptions have been made before proceeding, including:

- Only passenger cars (<6m) were considered in this study for simplicity reasons. Buses and trucks which would affect the characteristics (e.g., start-up lost time, saturation headways) of the discharging flow at signalized intersection were excluded;
- Drivers would like to queue as close to the stop line as possible and the lanes in the sorting area have the same possibility to be occupied;
- It was assumed that the research on left-turn traffic under right-hand driving rules (typically in USA, Europe and China) referenced in this study, can be fully applied to the right-turn traffic under left-hand driving rules as applies in South Africa.

3.2.2 Research design

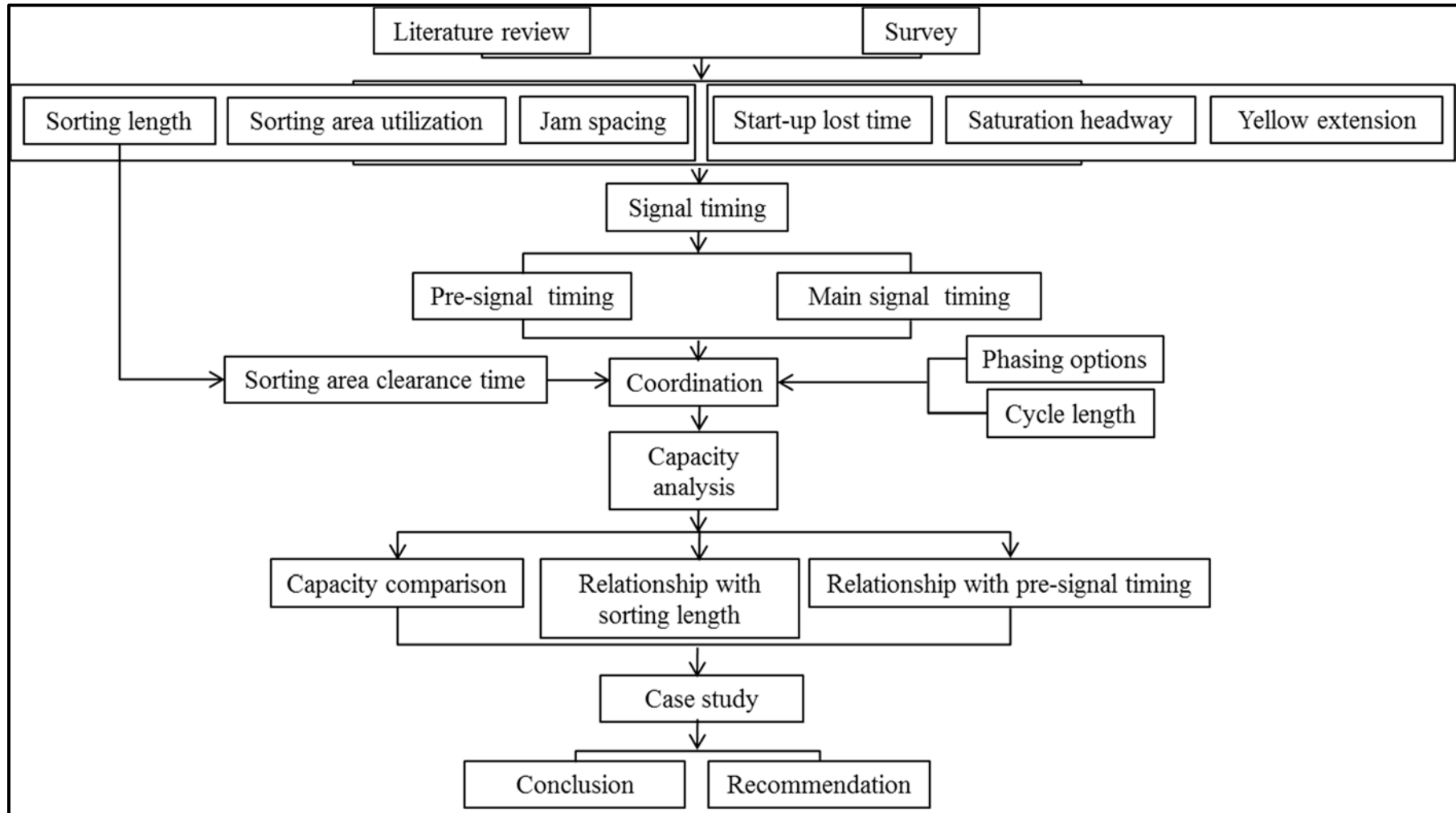


Figure 3.1 Research Design

3.2.3 Data collection

3.2.3.1 Jam spacing survey

This survey aims to get the average jam spacing. Data of this survey may be found in Appendix C.

3.2.3.1.1 Survey description

The intersection of R44 and Van Reede Rd is the site where this survey was conducted. Lane 3 of the southbound approach (refer to Figure 3.2) was chosen because there are fewer trucks when compared to lane 2 and no length restriction compared to the turning bays of lane 1 and lane 4.

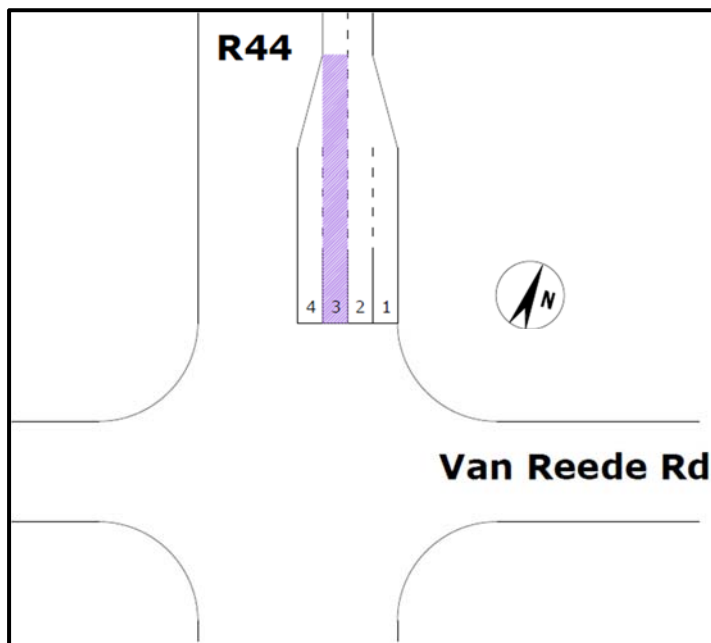


Figure 3.2 Site for Jam Spacing Survey

The peak hour periods were chosen to conduct the survey because vehicles are at a higher rate to stop and form queues during peak hours.

3.2.3.1.2 Sample size

Non-random sampling was used for this survey because not each unit had an established probability of being selected. Data of 111 traffic queues had been collected during the survey.

3.2.3.1.3 Instruments

- A 100-metre measuring tape,
- A long metal nail,
- A pen and a notebook, and
- Forms for recording data.

3.2.3.1.4 Procedures

1. Open the measuring tape from the stop line and fasten the start point with the metal nail;
2. Make the tape parallel to the lane line;
3. Count the number of stationary vehicles in the queue and read the value on the measuring tape where the rear bumper of the last vehicle of the queue is situated; and
4. Record this data on the designed form.

3.2.3.2 Lane change survey

Lane change is described in three parts (Olsen, 2003:13). It is the time and distance needed for a vehicle to 1) move from a straight-ahead position in the original lane and intercept the lane line, 2) completely cross that line, and 3) return to a straight-ahead position in the destination lane.

In a pre-signal controlled approach, some of the right-turn drivers have to make lane changes to enter the sorting area. This survey aims to study the utilization of the sorting area. It simulated the lane change manoeuvre of the last vehicle making the lane change and collected the data of extra space required in the sorting area to support drivers finishing this manoeuvre.

Figure 3.3 presents the lane change manoeuvre in the sorting area. When the signal (a VMS board showing movement arrows could be a better choice) turns green for one movement, the right-turn movement for example, through vehicles in lane 2 as shown in Figure 3.3 must stop after the pre-stop line while right-turn vehicles start filling the sorting area. Some of the right tuners have to make a lane change to acquire better positions as close to the main stop line as possible. The last vehicle making a lane change from lane 1 to the destination lane will need some extra space (the distance of $|y_1 - y_0|$ as shown in Figure 2.33) between its rear bumper and the

pre-stop line to finish the lane change with a straight-ahead position. This extra space is the wasted space of the sorting area, which cannot be used for storing vehicles.

Data of this survey may be found in Table 7.7 (Appendix D).

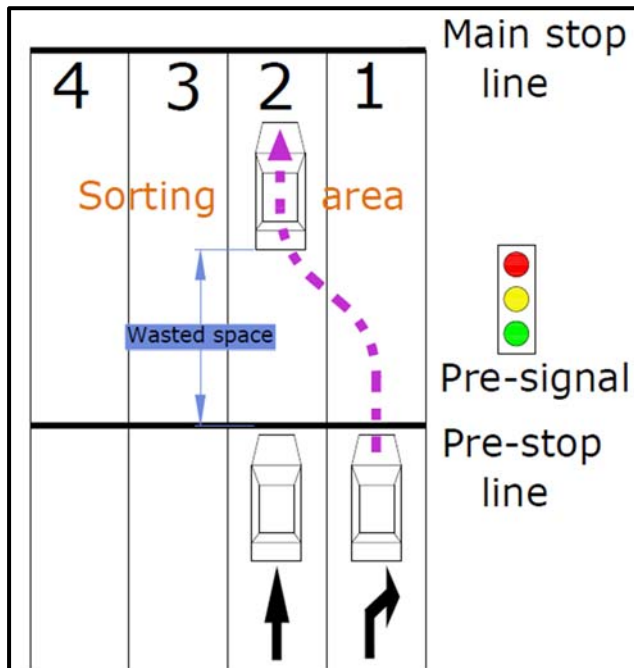


Figure 3.3 Lane Change Test in the Survey

3.2.3.2.1 Survey description

- The survey was conducted at the parking area of the Engineering Faculty on Sunday. There is enough space available for driving simulation in the parking area and few vehicle interruptions on weekend.
- Three drivers with different driving experience were chosen to do the test in an effort to simulate the composition of different drivers.
- Two cars with different length, a sedan (4.7m) and a hatchback (3.6) were chosen in an effort to simulate the composition of different passenger-cars in real environment.
- Three types of lane change manoeuvre were tested to simulate the lane change manoeuvre in a sorting area with different number of sorting lanes from 1 to 3, which correspond to lane change manoeuvre covering 2 lanes, 3 lanes and 4 lanes respectively.

3.2.3.2.2 Sample size

3 drivers with different driving experience drove two cars (a sedan and a hatchback) with different vehicle sizes to make lane changes covering different lanes for 5 times each. Table 3.1 lists the information of the drivers' driving experience and Table 3.2 presents the form used to record the data.

Table 3.1 Drivers' Driving Experience

	Finished mileage (km)	Licensed in	Driving years (year)
Driver A	39000	Feb., 2012	2
Driver B	21000	July, 2011	2.5
Driver C	5000	July, 2013	0.5

Table 3.2 Form of the Lane Change Survey Unit: m

Vehicle mode									
Covering 2 lanes				Covering 3 lanes			Covering 4 lanes		
Drivers No.	A	B	C	A	B	C	A	B	C
1									
2									
3									
4									
5									
I_w									
L_w									

3.2.3.2.3 Instruments

- A 4.7-metre long Audi A4 and a 3.6-metre long Ford KA,
- A few chalks,
- A 100-metre measuring tape,
- 3 drivers with different driving experience,
- A pen and some recording forms, and
- A data recorder.

3.2.3.2.4 Procedures

1. Draw four 3.2-metre (which is the common width of the lanes at intersections) lanes and a stop line (the pre-stop line at pre-signal).
2. Fasten the start point of the measuring tape. Open and make it parallel to the lane lines.
3. Park car 2 on lane 2 at the pre-stop line.

4. Driver A starts to drive car 1 on lane 1 and maintains a speed of around 10 km/h.
5. Driver A then starts the lane change manoeuvre as long as it is safe to change lane without colliding with the car parking on lane 2.
6. Driver A should steer the wheel in a quick but not uncomfortable way during that period.
7. Driver A should brake but must avoid making a sudden stop as soon as the vehicle goes straight in lane 2.
8. The recorder then records the value on the measuring tape where the rear bumper of the vehicle is situated.
9. Driver A drives car 1 to repeat the lane change manoeuvre of covering 2 lanes, 3 lanes and 4 lanes for 5 times.
10. Driver A then drives car 2 to repeat all what he has done on car 1 while car 1 should be parked at the place where car 2 parked before.
11. Driver B and driver C then repeat the same procedures as driver A did.

3.2.3.2.5 Testing speed

The test speed was set at 10 km/h which is a conservative value. The longitudinal distance $|y_1 - y_0|$ consumed to finish a one-lane change would increase as the speed increases.

Another reason that 10 km/h was used as the testing speed is because queued right-turn vehicles start to movements from stationary states when the pre-signal indicates them to change lanes.

3.2.3.3 Additional data

Data of Start-up lost time and headways should also be collected to study the signal time lost in a signal cycle and to support the signal timing of the pre-signal strategy.

Given there are many studies and data available locally and internationally, the data of start-up lost time and headways are collected from the available research portals rather than collected from the real site measurement.

Data of traffic counts and signal timings at the intersection of R44/Van Reede Rd is collected to support the case study. The Stellenbosch Municipality provided detailed

data of traffic counts and signal timings for the intersection of R44/Van Reede Rd. The location of the intersection may be found in Figure 3.4.

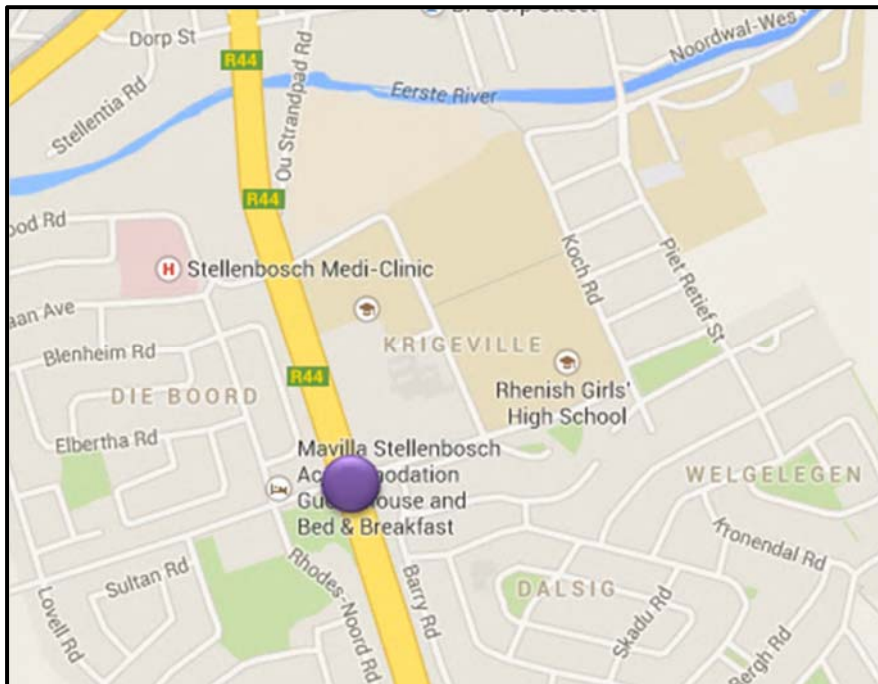


Figure 3.4 Intersection of R44/Van Reede Rd (Google Maps)

3.3 Summary

This chapter presents the research methodology for this study. Some basic assumptions are given and the structure of this study is presented in the research design. Sample sizes and procedures of the surveys are also described and explained here.

CHAPTER 4 ANALYSIS

4.1 Introduction

Signal timing and coordination of the pre-signal are studied in this chapter. The green time of the main signal based on sorting lanes is derived and optimal main green time is also given. Coordination based on different phasing options is also discussed. The period of pre-signal which could be used to “feed” the sorting area is investigated.

Based on the sorting length and the signal timing and coordination, capacity analysis is also conducted in this chapter. At last, potential problems of this proposed control method are estimated.

4.2 Signal timing and coordination

4.2.1 Important elements in signal timing

4.2.1.1 Start-up lost time

Total start-up lost time l_1 was assumed to be approximately 2 seconds in the Traffic Signal Timing Manual (Koonce, 2008:3-5). Average values ranging from 2.1 to 2.2 seconds for right-turn movements under leading phase control were suggested in a research (Bester & Varndell, 2002) based on some local intersections in Stellenbosch, South Africa. For this study, average start-up lost time is set to be the local value of 2.2 seconds.

It should be noted, as the start-up lost time used in this study is assumed to affect the first four vehicles while the successive vehicles would cross the stop line at saturation headway (TRB, 2010).

4.2.1.2 Saturation headway

As shown in Section 2.6.2, much research had been done on the saturation headway. Based on the research done by Bester and Varndell (2002), the saturation flow rates for two protected right-turn movements in their study were 1840 veh/h and 1920 veh/h, which corresponds to saturation headways of 1.96 seconds and 1.88

seconds respectively. The average value of the two average headways, 1.92 seconds, is used as the average saturation headway in this study.

4.2.1.3 Jam spacing

A survey based on a sample size of 111 queues at the intersections of R44/Van Reede Rd and R44/Safraan Rd suggested the average jam spacing S in the two intersections is 6.9 metre. The value may be found in Appendix C.

4.2.1.4 Yellow extension

A value of 2 seconds for yellow extension e is recommended by HCM 2010 (TRB, 2010:31-8).

4.2.1.5 Yellow change interval and red clearance interval

Yellow change interval, denoted as γ , usually has a range of 3 to 6 seconds. While red clearance interval, denoted as R_c , should be calculated according to the intersection width, vehicle length and the speed when the vehicle clear the intersection.

The yellow change interval and red clearance interval together form the interval between two phases. This interval is named as the change interval in the following context.

4.2.2 Optimal main green time

4.2.2.1 Introduction

The proposed pre-signal system actually does not affect the through movement too much. It just “borrows” part of the through lane(s) and allows the right-turn movement to use it (them) temporarily. After the right-turn vehicles have been served, through vehicles could simply proceed to occupy the sorting area without making any lane change. The only requirement for the main through green time is that it should meet the requirement as shown in Equation (14).

Therefore, the main signal timing for through movement is not discussed here. And the optimal main green discussed in this section specifically indicates the main right-turn green G_r .

In this section, the relationship between the **optimal main green time** G_r and the **length of the sorting area** L is derived. The optimal main green time may be defined as the green time duration which yields the highest vehicle outputs per green time unit for a given length of sorting area.

4.2.2.2 General main green timing

Because the pre-signal shifts right-of-way between the right-turn movement and the through movement, there should be no residue queue occupying the sorting area at the moment the main green starts to serve the next movement. This means the proceeding time should be provided long enough to serve all the vehicles in the sorting area.

The minimum time duration required to serve all the vehicles queuing in a fully occupied sorting area is the time duration between the initial main green and the moment the last vehicle in the queue crosses the main stop line. This minimum time duration could be calculated by:

$$t_m = i_N * h_s + l_1 \quad (10)$$

Where

t_m = minimum green required to clear a full sorting area (s),

i_N = number of vehicles that could be accommodated in the sorting area

However, the actual proceeding time available for vehicles at a signalized intersection should be the sum of the green time G and the yellow change interval γ . For those extreme cases, the driver who just pass the stop line at the very last instant of the yellow change interval would still not violate any traffic law.

But apparently, this is only an extreme case because yellow interval is not designed to be another part of green time. Therefore, the proceeding time here is defined as the sum of green time and the extension of effective green e which is only part of the yellow interval but not all of it. This is expressed in the following formulas.

$$G_r + e \geq t_m \quad (11)$$

$$G_t + e \geq t_m \quad (12)$$

Where:

G_r = main green for right-turn movement (s)

G_t = main green for through movement (s)

Substituting Equation(10) into Equation(11) and (12), the main green time could be derived.

$$G_r \geq i_N * h_s + l_1 - e \quad (13)$$

$$G_t \geq i_N * h_s + l_1 - e \quad (14)$$

For any given length of a sorting area, these two equations provide the main green time which should be provided to serve all the vehicles in the sorting area.

It may be noted that as the start-up lost time used in this study is assumed to affect the first four vehicles while the successive vehicles cross the stop line at saturation headways, the i_N , therefore, should meet the following requirement,

$$i_N \geq 4$$

The sorting area in this study must be long enough to accommodate at least 4 vehicles.

4.2.2.3 Optimal main green based on i_N

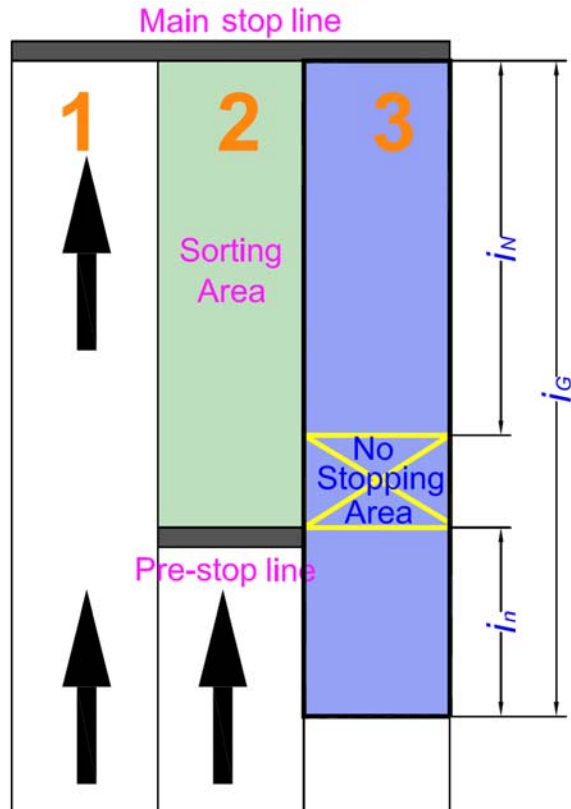


Figure 4.1 Number of Vehicles that Could Be Served During G_r

For a given G_r , the effective green E_r for right-turn vehicles could be derived from Equation (9),

$$E_r = G_r + e - l_1 \quad (15)$$

Where,

E_r = effective green time for right-turn vehicles (s).

The number of vehicles passing the main stop line in one right-turn lane may be calculated by,

$$i_G = \frac{E_r}{h_s} = \frac{G_r + e - l_1}{h_s} \quad (16)$$

Where,

i_G = number of vehicles that could be served during G_r in a right-turn lane.

As shown in Figure 4.1 (when all these vehicles were in a stationary queue), i_G is divided into two parts. Part one is the vehicles between the main stop line and the no stopping area. The total number of vehicles in part one is equal to the number of vehicles in the sorting area, which is i_N . Part two is the vehicles after the no stopping area, denoted as i_n . Thus,

$$i_G = i_N + i_n \quad (17)$$

Where,

$i_n = \text{the part of } i_G \text{ queuing after the no stopping area in one right-turn lane}$

Now, when considering the sorting area, the total number of vehicles passing the main stop line during G_r is the sum of the number of vehicles from the sorting area and the number of vehicles from the right-turn lane(s), which could be calculated by,

$$i = i_N * N + i_G * n \quad (18)$$

Where,

$i = \text{total number of vehicles passing the main stop line during } G_r,$

$N = \text{number of lanes in sorting area},$

$n = \text{number of right-turn lanes}.$

Substituting Equation (17) into the above formula to create,

$$i = i_G * (N + n) - i_n * N \quad (19)$$

Because,

$N > 0, \text{ and}$

$i_n \geq 0$

i could only reach the maximum value when,

$i_n = 0 \text{ (or, } i_N = i_G \text{)}$

This means that when the main green time is just enough to clear the sorting area, the total number of right-turn vehicles passing the main stop line reaches maximum during the given main green in one cycle.

Substituting $i_N = i_G$ this into Equation (16), we have the formula,

$$i_N = \frac{G_r + e - l_1}{h_s} \quad (20)$$

Rewrite this formula, we have,

$$G_r = i_N * h_s + l_1 - e \quad (21)$$

This formula gives the optimal main green which generates the highest vehicle outputs per green time unit for a given sorting length which could accommodate i_N vehicles.

4.2.2.4 Based on the ideal sorting area utilization

This assumption was used in all the former research (Xuan *et al.*, 2011; Xuan, 2011) when calculating the capacity of the pre-signal system. It was ideally considered that all the space in the sorting area could be used to accommodate and discharge vehicles. The number of vehicles which can be accommodated in one sorting lane then could be calculated by,

$$i_N = \frac{L}{S} \quad (22)$$

Where,

$L = \text{length of the sorting area, (m)}$

$S = \text{average jam spacing, (m/veh)}$

Substitute Equation (22) into Equation (21), the relationship between main green time and the length of the sorting area could be derived by,

$$G_r = \frac{L}{S} * h_s + l_1 - e \quad (23)$$

4.2.2.5 Based on the sorting area utilization in reality

4.2.2.5.1 Utilization of a sorting area

In this proposed pre-signal system, the right-turn vehicles have to make a lane change before they can occupy the sorting lane. Extra space between the rear bumper of the last vehicle which occupies the sorting lane and the pre-stop line should be provided for the vehicles to finish the lane change manoeuvre with a straight-ahead position in the destination lane. This extra space is the wasted space of the sorting lane, which cannot be used to store and discharge vehicles. The main green phase should not reserve green time for this extra space because actually no vehicle is served during that green period. The extra space is briefly shown in Figure 4.2.

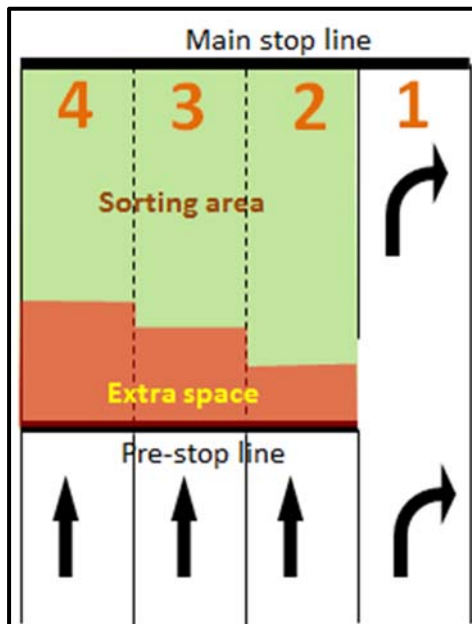


Figure 4.2 Utilization of the Sorting Area

Based on Equation (22), the number of vehicles which could be accommodated in the sorting area when considering the wasted space could be calculated by,

$$i_N = \frac{L - L_e}{S} \quad (24)$$

Where,

L_e = length of the wasted space in sorting area (m).

This extra space could not be ignored according to the data collected from the lane change test. Table 4.1 presents the average wasted space which should be provided for the drivers who made lane changes covering different lanes at a slow speed (around 10 km/h in the test) to get a straight-ahead position in the destination lane.

Table 4.1 Waste Space of a Sorting Area

	N=1	N=2	N=3
Average wasted space (m)	6	10	11

This means the sorting area is not fully utilised. For example, an approach was designed with 1 sorting lane ($N = 1$). If the sorting length is 60-metre long, the utilization of this sorting area and the main green is presented in Table 4.2. The utilization is around 90% in this case and could be lower when there are more sorting lanes because of the extra space needed in those cases.

Table 4.2 Example of Utilization of the Sorting Area

One lane sorting area		
Length of sorting area (m)	Wasted space (m)	Utilization
60	6	90%
Main green (s)	Wasted main green (s)	
22	2	91%

It should be noted, 10 km/h (refer to 3.2.3.2.5) is a very slow speed. The wasted space may increase for a vehicle to finish the lane change as the speed increases.

4.2.2.5.2 Solution to increase the utilization

This problem could be solved by simply adding this extra amount of space to the sorting area. And the main green should not be timed based on the whole length of the sorting area, but on the part which could be used to store vehicles.

4.2.2.5.3 Main green timing

When considering the extra space in the sorting area, the relationship between the main green time and the length of the sorting area could be derived from Equation (23) as follows,

$$G_r = \frac{L - L_e}{S} * h_s + l_1 - e \quad (25)$$

Rewriting the formula, it gives,

$$L = \frac{(G_r - l_1 + e)}{h_s} * S + L_e \quad (26)$$

Equation(25) gives the optimal green time which generates the highest vehicle outputs per green time unit for a given sorting length of L. Equation(26) presents the optimal sorting length which accommodates the maximum number of vehicles that could be served during the given main green time G_r .

4.2.3 Pre-signal timing

The pre-signal is a “feeder” which controls the access of vehicles coming into the sorting area. If not coordinated well, drivers may be held at the pre-signal, which leads to the waste of the main signal green time.

In order not to waste main green time, the pre-signal green timing should be long enough to fully fill the sorting area. This amount of right-turn green time depends on the total number of vehicles ($i_N * N$) which could be accommodated in the sorting area. Thus, the green time should meet the following conditions (similar to Equation(13)),

$$g_r \geq i_N * N * h_s + l_1 - e \quad (27)$$

Where,

$$g_r = \text{green time of pre-signal for right-turn movement, (s)}$$

It should be noted that this equation is based on the rule that the sorting area is always “fed” only by its neighbouring right-turn lane. This rule is made because conflicts would arise between vehicles coming from different lanes when they are “feeding” the sorting area.

The minimum pre-signal green time given in Equation(27) ensures the full use of the main green time, while the maximum available pre-signal green time determines the maximum capacity of the right-turn movement (In this case, all vehicles “fed” by pre-signal could be served by the main signal). It depends on the cycle length and phasing options. Different phasing options could have different available pre-signal green time. This available time would be discussed under different phasing options in Section 4.2.4.

4.2.4 Coordination

Coordination between the pre-signal and the main signal is necessary because they are too close to be considered separately. This coordination is one of the decisive factors which affect the efficiency of the pre-signal system. Cycle length, sorting area clearance time and the phasing options are the factors discussed here to coordinate the signals.

4.2.4.1 Cycle length

The prerequisite of coordinating the pre-signal and the main signal is that these signals must have the same cycle length. This is the critical requirement to ensure a smooth traffic flow so that drivers encounter less signal hindrance. Equation (28) presents the relationship between the two cycle lengths.

$$C_m = C_p \quad (28)$$

Where,

C_m = cycle length of the main signal (s),

C_p = cycle length of the pre-signal (s).

4.2.4.2 Sorting area clearance time

There are two clearance times with regards to the two movements in the proposed pre-signal system when using the sorting area, which are through vehicle clearance time and right-turn vehicle clearance time, denoted as t_{ct} and t_{cr} respectively.

As presented in the example of signal coordination in Figure 4.3, the sorting area clearance time is the time duration between the ends of the pre-signal yellow and the main signal yellow. This is to ensure that the last vehicle passing the pre-stop line at the end of the yellow interval could pass the main stop line before the main signal turns red.

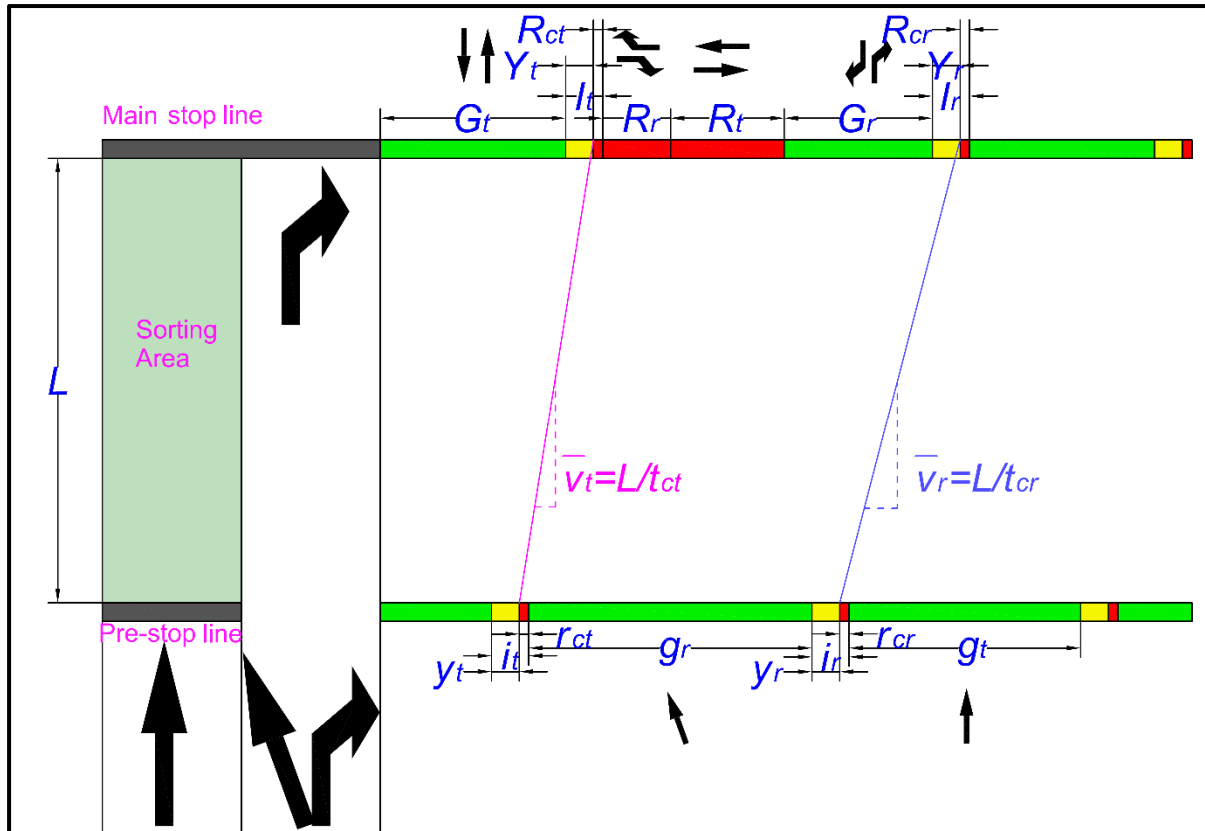


Figure 4.3 Sorting Area Clearance Time

Where,

t_{ct} = sorting area clearance time for through vehicles (s),

t_{cr} = sorting area clearance time for right-turn vehicles (s).

4.2.4.2.1 Through vehicle clearance time

The through clearance time should be no less than the time required for the last through vehicle to clear the sorting area. Using the average clearance speed, the through clearance time could be calculated by,

$$t_{ct} \geq \frac{L}{\bar{v}_t} \quad (29)$$

Where:

\bar{v}_t = average clearance speed of the last through vehicle (m/s).

It should be noted that the time consumed by a starting vehicle to pass a stop line is very complicated. It depends on many factors such as vehicle acceleration abilities

and driving behaviours. The average clearing speed and the average clearance time therefore should be collected from real sites.

Despite the complicated processes of the starting vehicle, Long (2000) stated in a research that an average acceleration rate of 1.44 m/s^2 was found for normal passenger cars to accelerate from 0 to 40.3 km/h, which is slightly less than another value of 1.5 m/s^2 found in another research.

It is therefore possible to estimate the clearance time by using this acceleration value. For instance, a vehicle will need 93 metres to accelerate (average accelerate rate, 1.5 m/s^2) from a speed of 0 to 60 km/h which is the limited speed of urban roads in South Africa for most cases. As shown in an example in Figure 4.4, a queue starting from the pre-stop line reaches a length of 93 metres (accommodates 13 vehicles with jam spacing, using Equation(22)) at the position A. Vehicles queuing after the position A could always enter the sorting area (when the pre-signal green time is longer enough to serve these vehicles) at the speed limit of 60 km/h and maintain this speed to clear the sorting area (In the proposed strategy of this study, these through vehicles do not need to stop after the main signal again by coordinating the two signals).

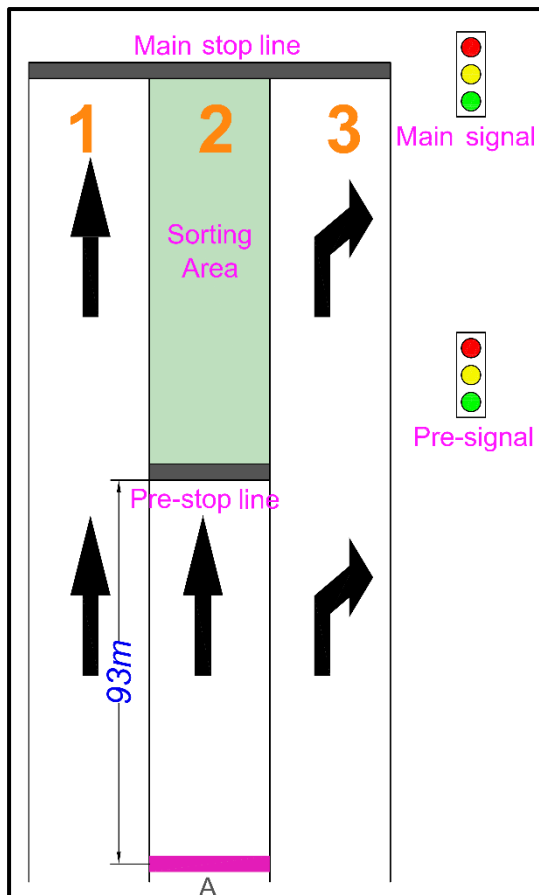


Figure 4.4 Example of Through Clearance Time

In this case, therefore, the last through vehicle clears the sorting area with the speed limit. The clearance time then may be calculated by,

$$t_{ct} \geq \frac{L}{v_l} \quad (30)$$

Where:

v_l = speed limit of the road (m/s).

The conditions which should be met before applying Equation(30) are summarised below:

- Average acceleration rate is 1.5 m/s^2
- The two signals should be coordinated well to ensure through vehicles passing the pre-stop line do not need to stop again after the main stop line
- For a typical approach with a speed limit of 60 km/h, the length of the queue after the pre-stop line should be no less than 93 metres (13 vehicles in

queue). And the pre-signal green time should be no less than 25 seconds (which could serve a queue of 13 vehicles)

4.2.4.2.2 Right-turn vehicle clearance time

The last right-turn vehicle in the sorting area starts moving from stationary and passes the main stop line with a turning speed. The right-turn clearance speed therefore is difficult to calculate because drivers would accelerate first and then decelerate to turn safely. Data collection should be done to analyse different clearance times based on different queue lengths.

$$t_{cr} \geq \frac{L}{\bar{v}_r} \quad (31)$$

Where,

\bar{v}_r = average clearance speed of the last right-turn vehicle (m/s).

4.2.4.2.3 Minimum clearance time

On one hand, the clearance time should be long enough to ensure that the sorting area is cleared before the main signal gives green to the next movement. Otherwise the vehicles failing to pass the main stop line during their phases must go with the vehicles from the next movement (e.g., right-turn vehicle should go straight if the next green phase is for through movement). On the other hand, the clearance time is actually part of the main green phase. When the extra green is used to ensure a cleared sorting area, the main green is wasted. Therefore, a trade-off exists between the cleared sorting area and signal efficiency.

When the priority has been given to efficiency, the minimum clearance time is the time duration which is just enough for the last vehicle to clear the sorting area.

4.2.4.2.4 Comparison between t_{ct} and t_{cr}

As been discussed above, the last through vehicle clears the sorting area with a high speed which could be the speed limit, while the last right-turn vehicle clears the same sorting area with a gradually increased speed which starts from 0 km/h and may have to decelerate before turning. This results in the different minimum clearance time of the same sorting area,

$$t_{cr} > t_{ct}$$

This fact would be used to analyse phasing options in the following context.

4.2.4.3 Phasing options of the main signal

Coordination also varies from one phasing option to another of the main signal. Some types of main signal phasing options do not fit to the pre-signal system, e.g., the one shown in Figure 4.5. The fact that right-turn and through vehicles using the sorting area in turn determines that the through phase and right-turn phase of the same approach must be separated.

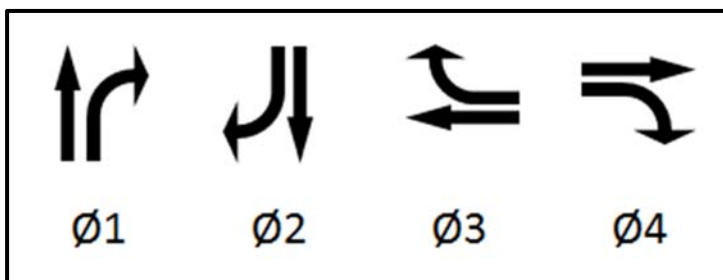


Figure 4.5 Typical Phasing Sequence that Do Not Fit the Pre-Signal System

The three types of phases discussed below are leading green right-turn phase, lagging green right-turn phase and swapping phase.

4.2.4.3.1 Leading green right-turn phase

In this phasing option, a designated green phase is given to the right-turn vehicles before the through phase. A typical leading phase is presented in Figure 4.6.

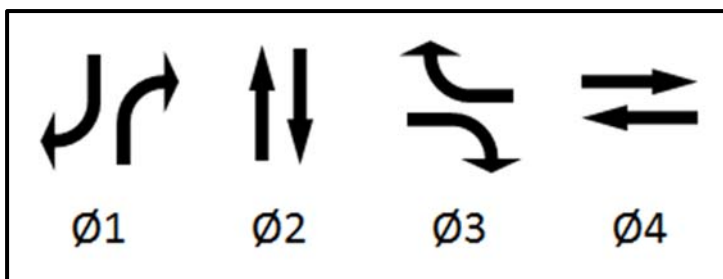


Figure 4.6 Typical Leading Phase

Figure 4.7 presents the time-space diagram for the leading phasing option.

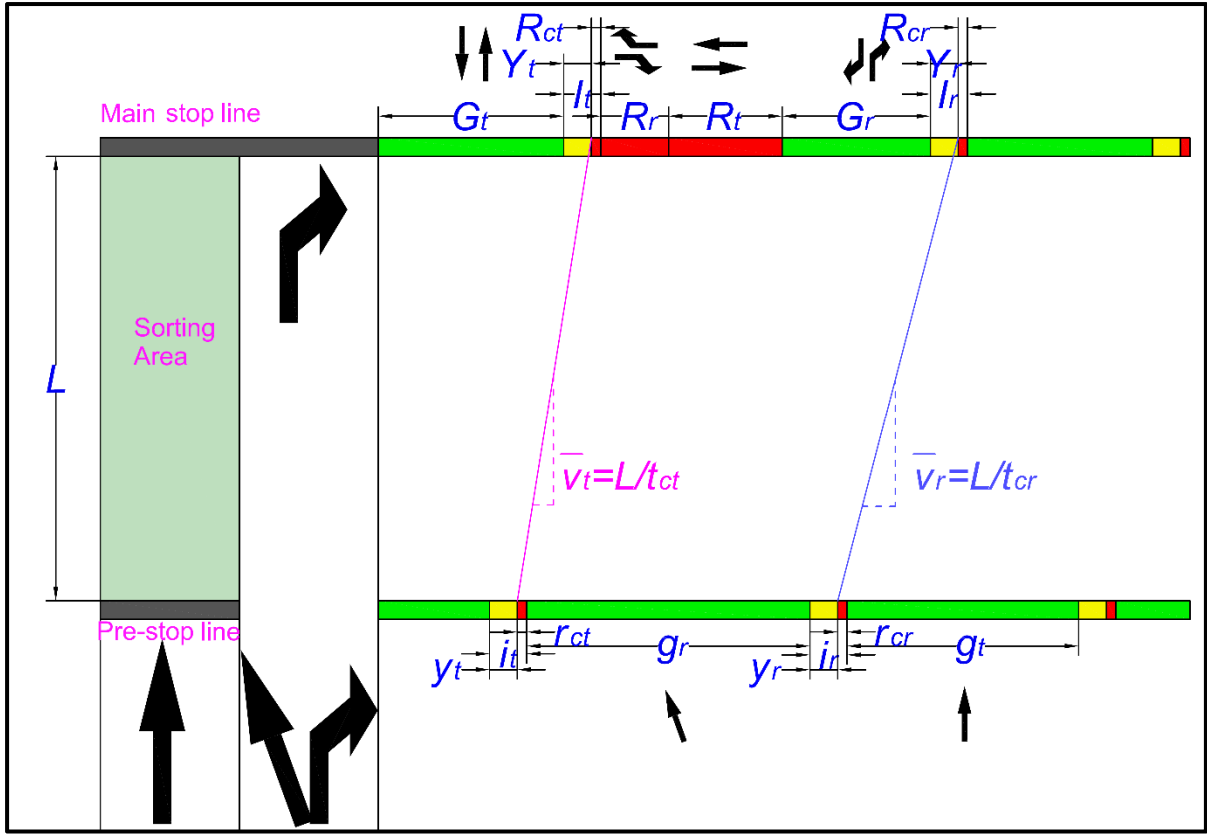


Figure 4.7 Space-Time Diagram of Leading Phasing Option

Where,

i_r = pre-signal change intervals for right-turn vehicles(s),

i_r = pre-signal change intervals for through vehicles(s),

I_r = main signal change intervals for right-turn vehicles (s),

I_t = main signal change intervals for through vehicles (s).

According to the time-space diagram Figure 4.7, the available pre-signal green time for right-turn vehicles g_r could be calculated by,

$$g_r = G_r + R_r + R_t + Y_r + R_{ct} + t_{ct} - t_{cr} - y_r - r_{ct} \quad (32)$$

Where,

R_r = right-turn phasing length on the crossing road (s),

R_t = through phasing length on the crossing road (s),

Y_r = yellow interval of the main right-turn phase (s),

y_r = yellow interval of the pre-signal right-turn phase (s),

R_{ct} = red clearance time of the main through phase (s),

r_{ct} = red clearance time of the pre-signal through phase (s).

This equation shows that there is quite a large amount of green time (g_r) available for the right-turn to “feed” the sorting area. For a given length of sorting area, this phasing option has a high ability to feed more sorting lanes. For example, if the time duration of $R_r + R_t$ is around 2 times of the G_r , then the available green time of the pre-signal g_r is around 3 times the G_r (suppose the value of $|t_{ct} - t_{cr}|$ would not affect the result too much). This means during the time duration of g_r , the right-turn vehicles could “feed” 3 sorting lanes.

4.2.4.3.2 Lagging green right-turn phase

In this phasing option, right-turn vehicles could only proceed during a designated right-turn green phase which is given after the through phase. A typical lagging phase is presented in Figure 4.8.

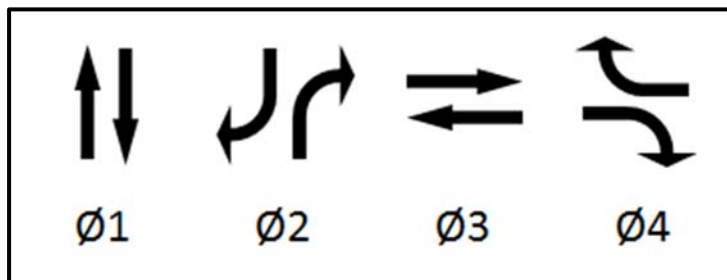


Figure 4.8 Typical Lagging Phase

For this phasing option, there will not be enough time for the right-turn vehicles to fully fill the sorting area. The first vehicle from the pre-signal could not even reach the main stop line when the main signal turns green for the right-turn movements. The reason for this is discussed below.

Figure 4.9 presents the space-time diagram for the lagging phasing option.

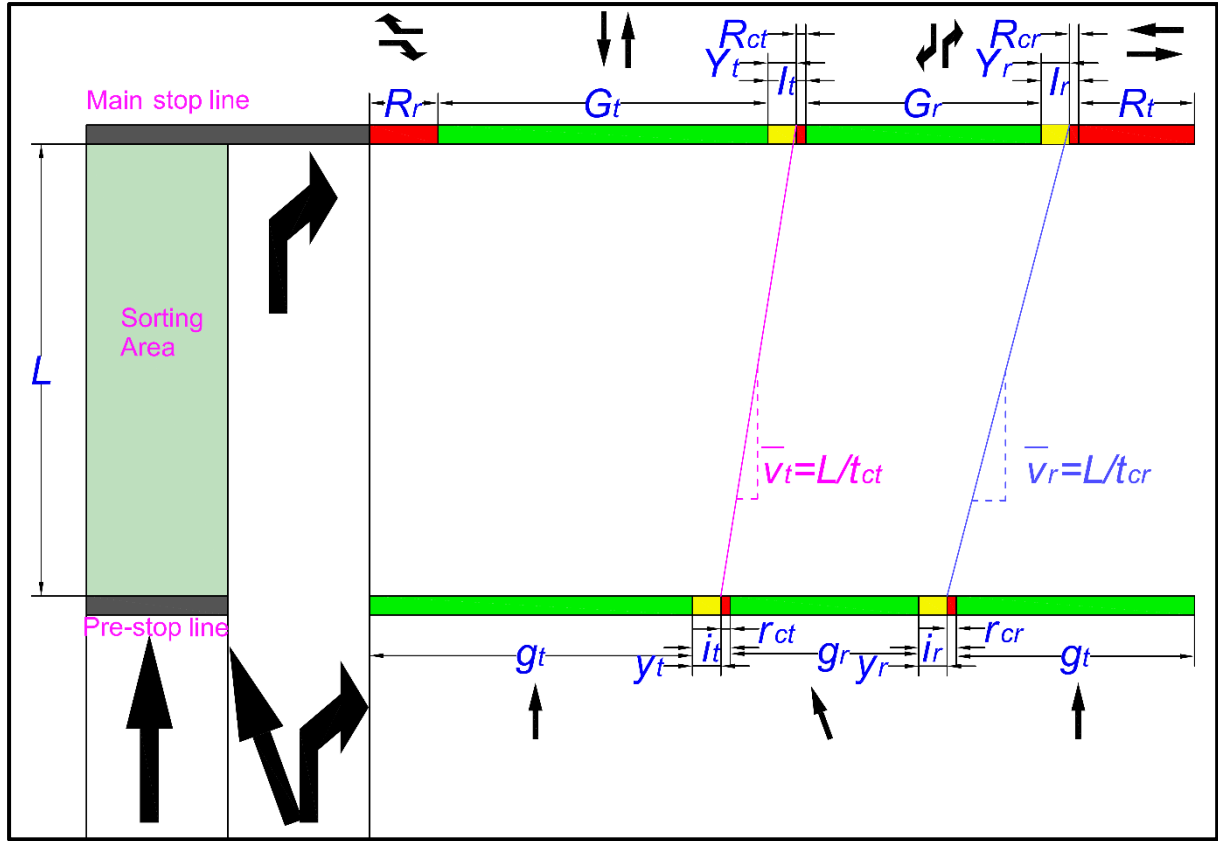


Figure 4.9 Space-Time Diagram of Lagging Phasing Option

The available pre-signal green time for right-turn vehicles g_r could be calculated by,

$$g_r = G_r + Y_r + R_{ct} + t_{ct} - t_{cr} - y_r - r_{ct} \quad (33)$$

Supposing uniform yellow intervals and red clearance intervals are used ($Y_r = y_r$ & $R_{ct} = r_{ct}$), then the g_r would be,

$$g_r = G_r + t_{ct} - t_{cr} \quad (34)$$

The g_r then would be shorter than G_r (which is because $t_{cr} > t_{ct}$). Therefore, part of the G_r is wasted because the pre-signal could not fully fill the sorting area. For this reason, the proposed pre-signal system could not perform well under this phasing option.

Another reason that this phasing option would not be functional in the proposed pre-signal strategy is because of the high speeds (usually the limited speeds under heavy traffic conditions as discuss before) at which the through vehicles pass the pre-stop line at the end of the through phase. If any of these drivers violate the red of the pre-signal, it could collide with the right-turn vehicles which are making lane

changes into the sorting area. This phasing option has a higher potential risk of accident for the proposed pre-signal system.

4.2.4.3.3 Phase swapping option

This phasing option is known as it swaps the sequence of the right-turn phase and the through phase as shown in Figure 4.10.

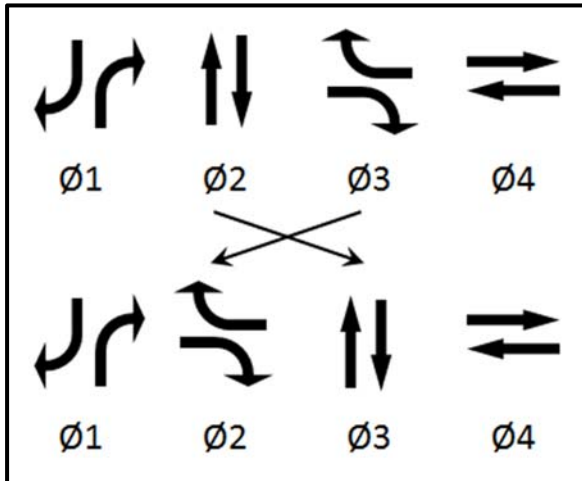


Figure 4.10 Phase Swapping Option

Figure 4.11 presents the time-space diagram for the phase swapping option.

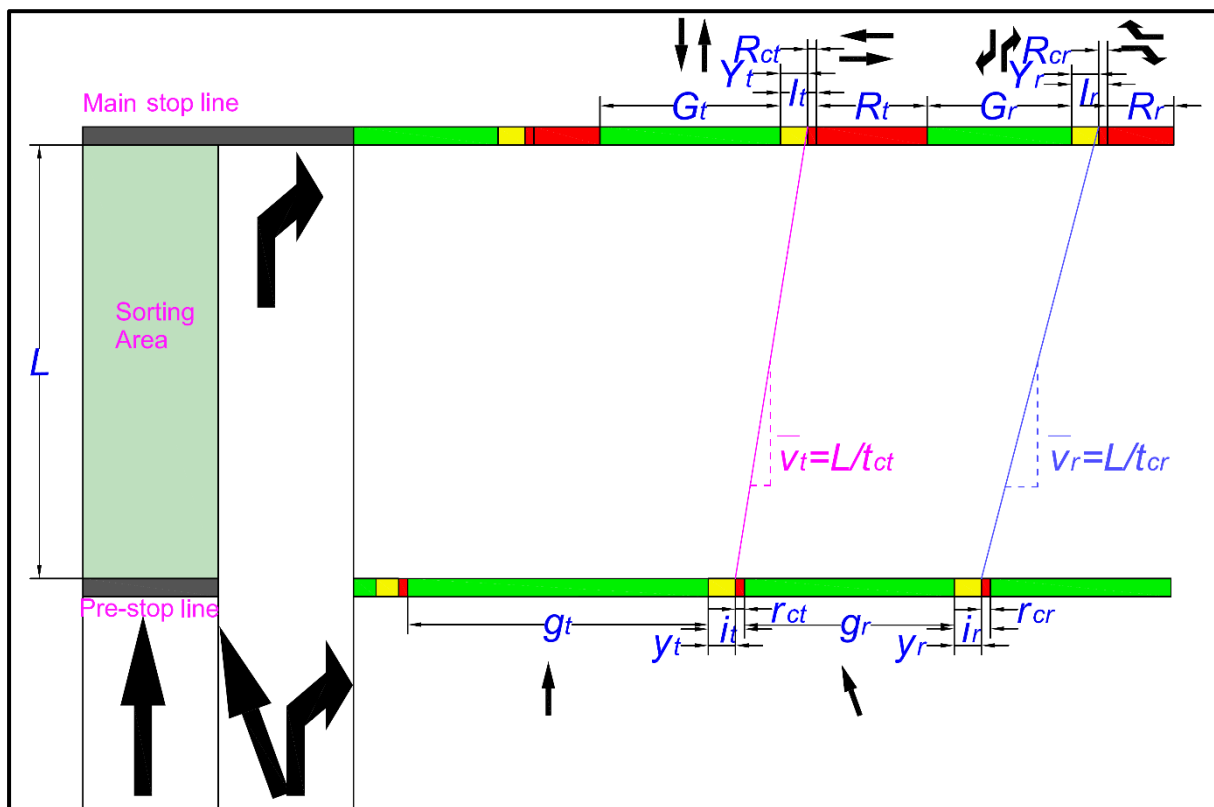


Figure 4.11 Space-Time Diagram of Phase swapping Option

The available pre-signal green time for right-turn vehicles g_r could be calculated by,

$$g_r = G_r + R_t + Y_r + R_{ct} + t_{ct} - t_{cr} - y_r - r_{ct} \quad (35)$$

For this phasing option, there is still a large amount of green time (g_r) available for the right-turn to “feed” the sorting area, although it is not as much as the one in the leading phasing option.

4.3 Capacity analysis

Capacity has been compared between the approach designed with the proposed pre-signal strategy and the conventional signal timed approach in this section. The relationships between the capacity of the right-turn movement and the sorting length are studied under different main signal timing options. At last, values are recommended for given sorting lengths.

4.3.1 Capacity benefit for the through movement

It should be noted that the proposed pre-signal strategy would not reduce through capacity. Through vehicles waiting after the pre-signal could simply proceed to occupy the sorting area by following the last right-turn vehicle when it starts to move. Through vehicles could always occupy the sorting area and be discharged after the main signal turns green for through vehicles just as there is no pre-signal. On the contrary, if the pre-signal gives green to through vehicles just a few seconds before the main through signal turns green, through vehicles then do not need to stop again after the main signal but proceed and pass the main stop line at speed. Then the capacity is actually increased because of the start-up lost time is being reduced in this case. The case study in CHAPTER 5 shows more about this.

One factor which could reduce the through capacity happens when the main green gives extra green time to the last through vehicle to clear the sorting area. When compared to conventional signal timing option, no vehicles are served during this extra time periods which are used to ensure a cleared sorting area. Studies on sorting area clearance time therefore, still need to be done.

4.3.2 Capacity benefits

Right-turn capacity is compared between the right-movements with and without pre-signal under the condition of the same cycle length and main green time.

4.3.2.1 Capacity of an approach with pre-signal

The capacity of a right-turn movement in one signal cycle is the number of vehicles passing the main stop line during the main green period. Suppose the sorting area is always fully filled except the extra space provided for vehicles to finish their lane change manoeuvre. There would be i_N vehicles served in the sorting lane(s) and i_G vehicles served in the right-turn lane(s) in one signal cycle. Therefore, the total number of vehicles served in one signal cycle would be calculated by,

$$i = i_N * N + i_G * n, (i_N \leq i_G) \quad (36)$$

For a main signal with a cycle length of C_m , the right-turn capacity in one hour may be calculated by,

$$q_{rp} = (i_N * N + i_G * n) * \frac{3600}{C_m}, (i_N \leq i_G) \quad (37)$$

Where,

$$q_{rp} = \text{right-turn capacity under pre-signal option} \left(\frac{veh}{h} \right).$$

4.3.2.2 Capacity of an approach with conventional signal

Suppose an approach under conventional signal control uses the same cycle length and the same main green time. Then, the right-turn capacity in the conventional option could be derived by,

$$q_{rc} = i_G * n * \frac{3600}{C_m}, (i_N \leq i_G) \quad (38)$$

Where,

$$q_{rc} = \text{right-turn capacity under conventional signal option} \left(\frac{veh}{h} \right).$$

4.3.2.3 Capacity benefit

Comparing the capacity of an approach with and without the installation of pre-signal (Equation(37) minus Equation(38)), we have,

$$\Delta q = i_N * N * \frac{3600}{C_m}, (i_N \leq i_G) \quad (39)$$

Where,

$$\Delta q = \text{the capacity benefited from installing a pre-signal } \left(\frac{veh}{h}\right)$$

This equation shows that the benefit of the pre-signal comes from the sorting area. The capacity benefit reaches maximum when $i_N = i_G$. This is a situation that the optimal main green is applied (refer to section 4.2.2).

4.3.2.4 Benefit rate

Benefit rate could be derived if we compare the maximum benefit capacity Δq_{max} with the capacity of the approach without pre-signal.

$$\frac{\Delta q_{max}}{q_{rc}} = \frac{i_N * N * \frac{3600}{C_m}}{i_N * n * \frac{3600}{C_m}} = \frac{N}{n} \quad (40)$$

The values of $\frac{\Delta q_{max}}{q_{rc}}$ are listed below under conditions of different right-turn and sorting lanes (different n and N).

Table 4.3 Capacity Comparison

N \ n	1	2	3
1	1.00	2.00	3.00
2	0.50	1.00	1.50
3	0.33	0.67	1.00

4.3.3 Relationship between capacity and sorting length

4.3.3.1 For any given main green

When studying Equation(39), it could be found that for any given main green, the benefit capacity Δq increases as i_N increases. In other words Δq increases as the

length of the sorting area increases. The benefit capacity reaches maximum when $i_N = i_G$, which means the main green yields the highest outputs in a green time unit.

4.3.3.2 Maximum benefit capacity of a given green ratio

The main green ratio for the right-turn movement could be calculated by,

$$\alpha = \frac{G_r}{C_m} \quad (41)$$

Where,

$\alpha = \text{ratio of main green time to cycle length.}$

As discussed above, the maximum benefit capacity could be reached when $i_N = i_G$ which mean the optimal main green is applied. Substituting Equation(41), Equation(21) and Equation(24) into Equation(39), we have,

$$\Delta q_{max} = \frac{3600 * \alpha * N}{h_s + \frac{(l_1 - e) * S}{L - L_e}}, (i_N \geq 4, L \geq 4 * S + L_e) \quad (42)$$

Substitute, the values of h_s , l_1 , e and S as discussed in Section 4.2.1, into Equation(42), and it gives,

$$\Delta q_{max} = \frac{3600 * \alpha * N}{1.92 + \frac{6.9}{5 * (L - L_e)}}, (L \geq 4 * S + L_e) \quad (43)$$

When studying Equation(43), it may be found that for any given α , N and n , the maximum benefit capacity Δq_{max} , increases very slowly as the L increases. This is because (use $N=1$, $L_e = 6$ as an example),

$$\frac{3600 * \alpha}{1.97} < \Delta q_{max} < \frac{3600 * \alpha}{1.92}, (L \geq 34) \quad (44)$$

Therefore, the maximum capacity (reached when the optimal green time are applied) benefitting from the pre-signal does increase as the sorting length increases, but not significantly. While the green ratio and the number of sorting lanes are the factors which affect the maximum benefited capacity significantly.

4.3.4 Recommended values

Based on sorting length, right-turn capacity is calculated and signal timing is also recommended in this section. An example of maximum capacity benefit (Δq_{\max}) is given in a case of green ratio equals to 0.2. The recommended value of clearance time should be given based on real site surveys which still need to be done in the future.

As presented in Table 4.4, the extra capacity generated from the installation of pre-signal system is significant. E.g., for a given sorting length of 75 metres, the optimal main green time is 19 seconds and the right-turn capacity could increase by 372 veh/h for one sorting lane, 744 veh/h for two sorting lanes and 1116 veh/h for three sorting lanes.

Table 4.4 Recommended Values

		i_N (veh)	$L(m)$			$G_r (s)$	minimum $g_r (s)$			$\Delta q_{max} (veh/Cycle)$			$\Delta q_{max} (veh/h)$		
			$N=1$	$N=2$	$N=3$		$N=1$	$N=2$	$N=3$	$N=1$	$N=2$	$N=3$	$N=1$	$N=2$	$N=3$
$l_1 (s)$	2.2	4	34	38	39	8	8	16	23	4	8	12	366	733	1099
$e (s)$	2	5	41	45	46	10	10	19	29	5	10	15	368	736	1104
$h (s)$	1.92	6	47	51	52	12	12	23	35	6	12	18	369	739	1108
$s (m)$	6.9	7	54	58	59	14	14	27	40	7	14	21	370	741	1111
		8	61	65	66	16	16	31	46	8	16	24	371	742	1113
		9	68	72	73	17	17	35	52	9	18	27	372	743	1115
		10	75	79	80	19	19	39	58	10	20	30	372	744	1116
N	Le(m)	11	82	86	87	21	21	42	63	11	22	33	372	745	1117
1	6	12	89	93	94	23	23	46	69	12	24	36	373	745	1118
2	10	13	96	100	101	25	25	50	75	13	26	39	373	746	1119
3	11	14	103	107	108	27	27	54	81	14	28	42	373	746	1119
		15	110	114	115	29	29	58	86	15	30	45	373	746	1120
G_r/C_m	0.2	16	116	120	121	31	31	62	92	16	32	48	373	747	1120
		17	123	127	128	33	33	65	98	17	34	51	374	747	1121
		18	130	134	135	35	35	69	104	18	36	54	374	747	1121
		19	137	141	142	37	37	73	109	19	38	57	374	748	1121
		20	144	148	149	39	39	77	115	20	40	60	374	748	1122

4.4 Potential problems

Here are some potential problems at intersections installed with the pre-signal strategy:

- Confusion. Drivers may not fully understand this control method and they may be confused when driving to an intersection installed with pre-signal. Traffic signs should be clearly installed upstream of the pre-signal to inform the drivers.
- Blockage. The neighbouring intersection situating upstream of the pre-signal could be blocked when the distance between the two intersections are not long enough or when the heavy traffic surges happened in some extreme cases.
- Capacity waste. When drivers fail to clear the sorting area during their green time, they are supposed to go with the next movement which is going to use the sorting area. However, if drivers refuse to do so and still wait for their next green phase, all the vehicles of the next movement using the sorting area will be blocked. Green time and Capacity are wasted in this case.

To improve these problems, education on drivers are necessary before installing pre-signals to intersections. Traffic signs upstream of the pre-signal are recommended to inform the drivers. Enforcement are also very important to avoid unnecessary congestions.

4.5 Summary

4.5.1 Optimal main green time

Equation(25) gives the optimal green time which generates the highest capacity benefit per green time unit for a given sorting length of L . Equation(26) presents the optimal sorting length accommodating the maximum number of vehicles which could be served during the given main green time G_r .

4.5.2 Sorting area clearance time

Sorting area clearance time should be provided to ensure a cleared sorting area before the main signal serves the next movement. It's a trade-off between efficiency of main green time and a cleared sorting area because extra green time of main signal allocated for clearing the sorting area is actually wasted.

Sorting area clearance time designed for right-turn vehicles should be longer than that designed for through vehicles. Surveys should be done in the future to analyse the sorting area clearance time.

4.5.3 Phasing options

The fact that right-turn and through vehicles using the sorting area in turn determines that the through phase and right-turn phase of the same approach must be separated in a signal stage. Leading phasing option and phase swapping option are two options that could fit the pre-signal concept proposed in this study. The leading phasing option, however, has an ability to “feed” more right-turn vehicles into the sorting area because there is more available green time for the pre-signal.

4.5.4 Benefits from installing pre-signal

Equation (39) shows that right-turn movements could always benefit from installing pre-signals in terms of capacity. For a given main green time and cycle length, the capacity benefit increases as the length of the sorting area and the number of sorting lanes increase. Equation (43) shows that for a given green ratio, sorting length does affect the maximum capacity benefit, but not significantly. Furthermore, Table 4.3 shows that the maximum benefit rate of capacity decreases as n increases while it increases as N increases.

CHAPTER 5 CASE STUDY

5.1 Introduction

Benefits of the proposed pre-signal strategy were analysed theoretically in CHAPTER 4. In this chapter, the pre-signal strategy is applied to an intersection in a simulated environment.

Basic data of the intersection (e.g., intersection configuration, traffic counts and signal timing) are collected to support the simulation. The micro-simulation software VISSIM is used to conduct the simulation.

In the following context, the “before” model represents the model without the proposed pre-signal system; the “after” models represents the models with the proposed pre-signal system.

5.2 Simulation software

Micro-simulation software VISSIM is used in this study. A brief introduction of VISSIM could be found on the PTV official website, which is cited below:

“Whether comparing junction geometries, analysing public transport priority schemes or considering the effects of certain signalling – PTV Vissim allows you to simulate traffic patterns exactly. Motorised private transport, goods transport, rail and road related public transport, pedestrians and cyclists – as the world's leading software for microscopic traffic simulation, PTV Vissim displays all road users and their interactions in one model. Scientifically sound motion models provide a realistic modelling of all road users.

The software offers flexibility in several respects: the concept of links and connectors allows users to model geometries with any level of complexity. Attributes for driver and vehicle characteristics enable individual parameterisation. Furthermore, a large number of interfaces provide seamless integration with other systems for signal controllers, traffic management or emissions models.

PTV Vissim is rounded off with comprehensive analysis options, creating a powerful tool for the evaluation and planning of urban and extra-urban transport infrastructure.

For example, the simulation software may be used to create detailed computational results or impressive 3D animations for different scenarios. It is the perfect way to present convincing and comprehensible planned infrastructure measures to decision-makers and the public.”

5.3 Site description

5.3.1 Basic information

The intersection is at R44 and Van Reede Rd, Stellenbosch, South Africa. The location is depicted in Figure 3.4 and the layout is briefly presented below.

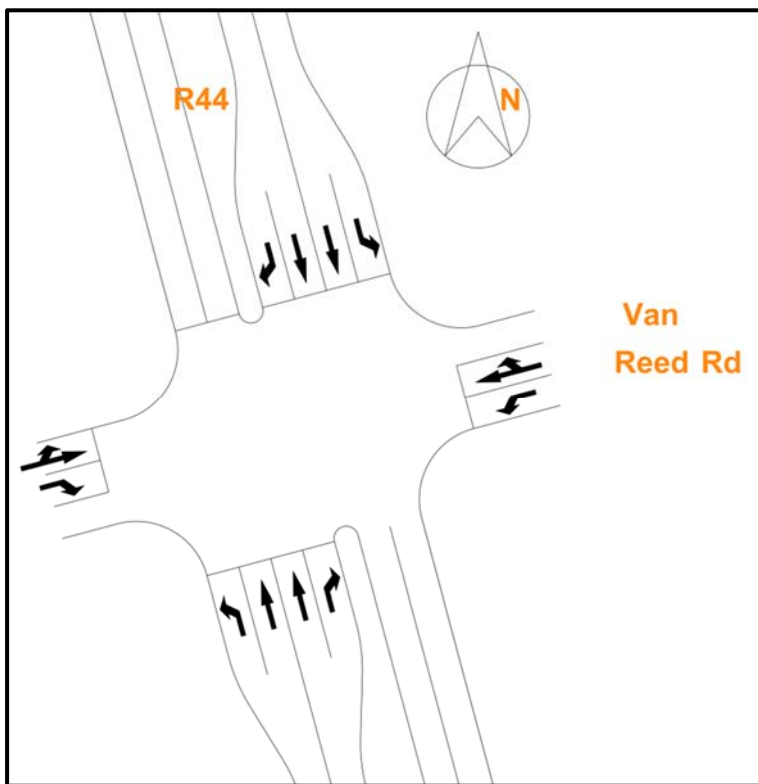


Figure 5.1 Layout of R44/Van Reede Rd

This is one of the major bottlenecks in the local road network around Stellenbosch. As shown in Figure 5.2, both school (more than 4 schools in the vicinity) traffic and commuting traffic need to turn right at the northbound approaching leg of the intersection during the morning peak hours of weekdays.

Long queues were observed at the northbound approaching leg of the intersection during the morning peak. Right-turn demand is relatively high and only one right-turn lane is provided in this intersection. Furthermore, the spacing between this

intersection and the intersection to the south is around 1 km which is long enough to apply the pre-signals. Theoretically, this intersection meets most of the requirements of installing the proposed pre-signal system.

One limitation is that there is only one exit lane on the westbound approaching leg (refer to Figure 5.3). It should be expanded into two lanes before applying the pre-signal.



Figure 5.2 Right-Turn Traffic Stream at the Northbound Approaching Leg of the Intersection



Figure 5.3 Only One Exit Lane on the Westbound Approaching Leg (Google Maps)

The Stellenbosch municipality provided the traffic counts and signal timing options of this intersection. The 15-minutes based traffic volume indicates that the peak hour in the morning occurred between 7:00-8:00 (on Wednesday, 10th Apr. 2013). This peak hour is chosen as the traffic input in the simulation. The traffic counts and signal timing plans are found in Appendix E.

5.3.2 Problems

During the morning peak, the large demand for right-turn traffic of the northbound approaching leg consumes a large part of the available green time of the intersection. A long queue was observed on the northbound approaching leg. The heavy right-turn demand also led to the opposing through traffic experiencing long delay when waiting to be served.

The 15-minute based traffic counts suggest that there are 4 critical movements in the total 12 in terms of peak hour traffic volume. These 4 critical movements are coded below for easy referencing.

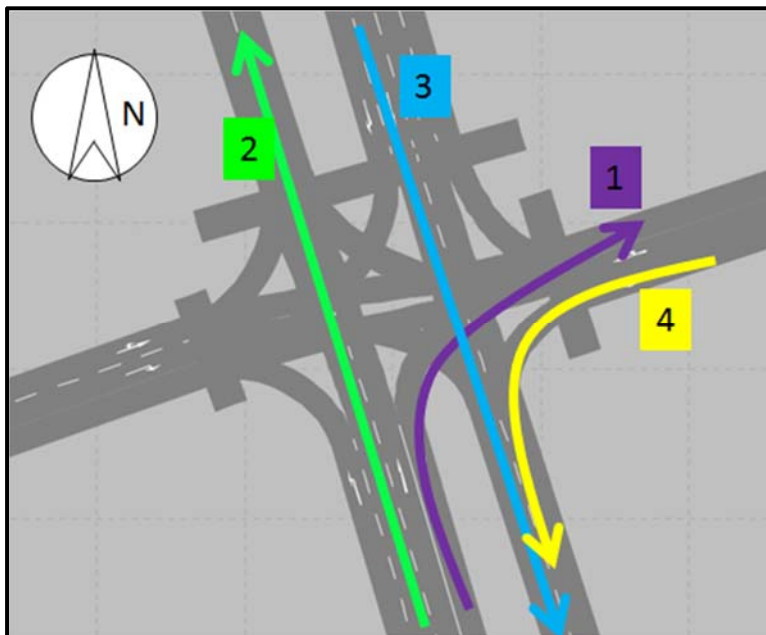


Figure 5.4 Coding of the Four Critical Movements

Where,

Code 1 represents right-turn movement of the northbound approach

Code 2 represents through movement of the northbound approach

Code 3 represents through movement of the southbound approach

Code 4 represents left-turn movement of the westbound approach

VISSIM records queue length on an approach basis (not based on each movement of the approach), which means only queue length of the approach could be recorded. The queue counters on the two approaching leg on R44 are coded as shown in Figure 5.5.

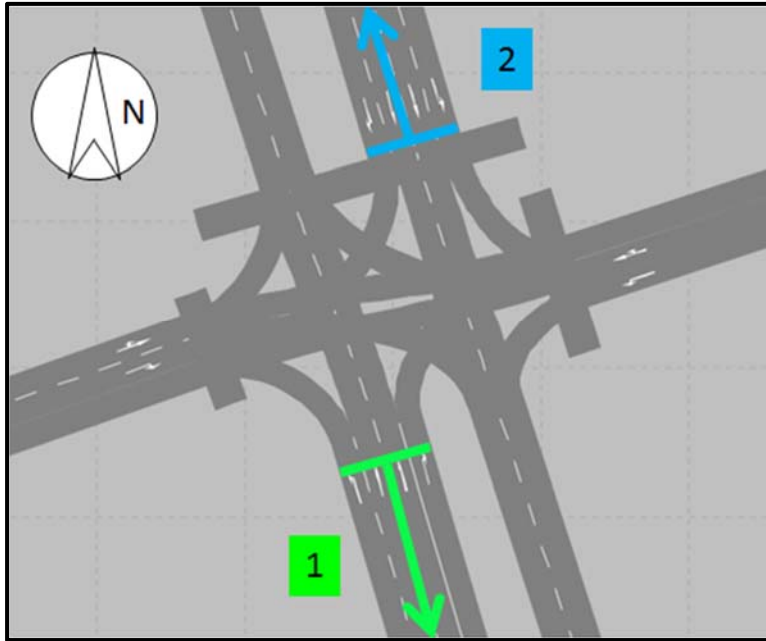


Figure 5.5 Coding of the Queue Counters

Where,

Code 1 represents the queue counter on the northbound approach

Code 2 represents the queue counter on the southbound approach

The movements and queues mentioned in the following context would use the codes defined above. For instance, right-turn movement of the northbound approach would be simply called movements 1. The queue counter on the northbound approach would be called queue counter 1.

5.3.2.1 Traffic demand

The northbound approach suffered heavy congestion during the morning peak hour. The movement 1 was served at a flow rate of 680 veh/h. The volume of movement 2 reached 1385 veh/h. Vehicles in queues were observed failing to pass the stop line in one cycle. Therefore, the traffic demand should be greater than the traffic volume counted.

The traffic volume of movement 3 was 1165 veh/h and volume of movement 4 was 643 veh/h.

5.3.2.2 Lanes

The layout of the intersection has not been changed from the moment when the traffic volume was collected. There are two through lanes in the northbound approaching leg, one left-turn bay and one right-turn bay. The turning bays are extended from the two lanes at around 80 metres upstream of the stop line.

Right turners were found using the right shoulder as an extension of the right-turn bay during the survey. This driving behaviour releases the pressure of the approach because when the right-turn bay is fully occupied, right-turn vehicles queuing in the shoulder would not block the through lane (refer to the case of overflow presented in Figure 2.6).

Therefore, the right-turn bay is extended to simulate this driving behaviour during the simulation.

5.3.2.3 Signal timing

A cycle length of 144 seconds was used at this intersection.

The protected green time allocated for movement 1 reached 54 seconds which corresponds to a green time ratio of 0.375. The right-turn traffic consumed a large part of green time. The green time allocated for movement 2 was 56 seconds.

The green time allocated for the movement 3 was 39 seconds which corresponds to a green time ratio of 0.271.

5.3.2.4 Volume to capacity ratio

The capacity of movement 1 was 703 veh/h (saturation headway is 1.92s) and the volume to capacity ratio was 0.97.

Applying the average saturation flow rate of the movement 3, 2044 veh/h (Bester & Meyers, 2007), the capacity of the two through lanes provided for movement 3 should be 1107 veh/h. Then the volume to capacity ratio of the through movement was 1.05.

It was found that both movements were running at a volume to capacity ratio of around 1 which indicates the full utilization of cycle capacity and is considered as capacity failure (TRB, 2010:18-6).

5.4 Apply the proposed pre-signal strategy

5.4.1 Lanes

5.4.1.1 Sorting lane

Using the proposed pre-signal strategy, part of the through lane which is next to the right-turn lane of the northbound approaching leg is designed as a sorting area. To use the sorting area, lane changes are forbidden for all vehicles except those vehicles which could make lane changes and enter the sorting area at the no stopping area (refer to Figure 5.6).

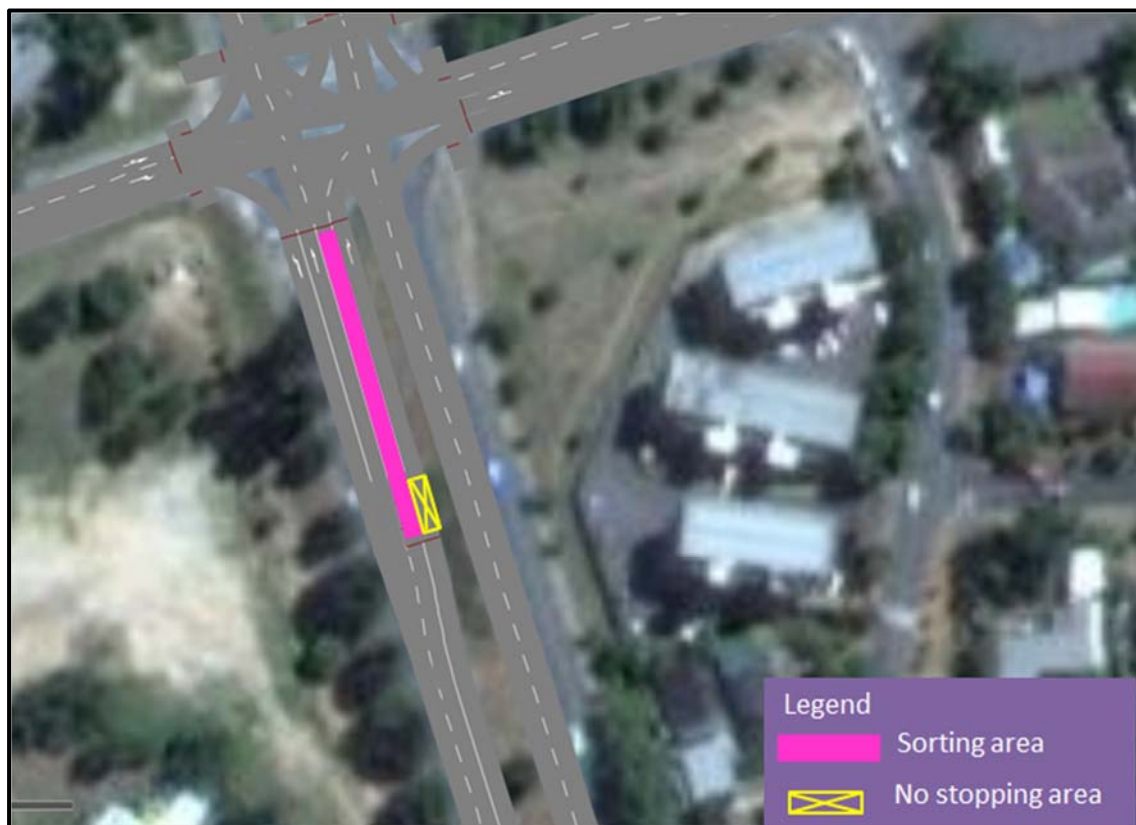


Figure 5.6 Lane Changes Are Allowed for Vehicles from the No Stopping Area

5.4.1.2 Exit lane

As one of the limitations of the proposed pre-signal strategy, the number of exit lanes should be adequate to accommodate vehicles from the increased discharging lanes.

Therefore the exit lane on the westbound approaching leg is assumed that it could be expanded into two lanes. The expansion of the exit lane is presented in Figure 5.7.



Figure 5.7 Expansion of the Exit Lane

5.4.1.3 Right-turn lane

Right-turn drivers of movement 1 always use the right shoulder and this releases the pressure of the approach. Therefore, the right-turn bay is extended to simulate this driving behaviour both in the “before” and “after” models.

5.4.2 Signal and sorting length

This intersection is semi-articulated during the morning peak hour. For the reason of reducing variables and focusing on the main problems, it is treated as a pre-timed intersection.

Furthermore, this intersection is one of the coordinated intersections on R44 around Stellenbosch. Therefore, when applying the proposed pre-signal strategy, the following requirement should be met to still coordinate the intersections after the installation of the pre-signal strategy:

1. The signal cycle length remains the same;
2. The phase sequence should not be changed; and
3. The green time for through movements on R44 should be the same or almost the same as the “before” model.

5.4.2.1 Phasing option

The leading phasing option was applied in the “after” models. The phasing sequence is illustrated by Figure 5.8.

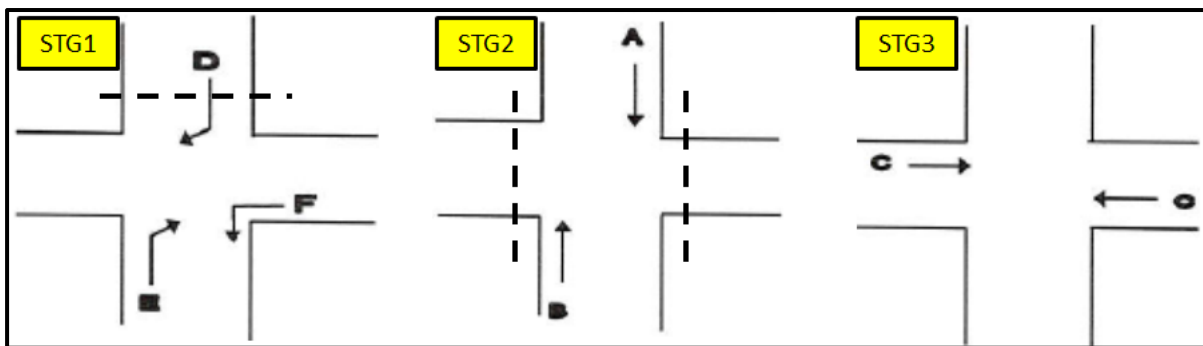


Figure 5.8 Phase Sequence in the After Models

5.4.2.2 Signal timing

In the “before” model, the green time for movement 2 is 56 seconds. In order to coordinate the signals on R44, the stage 2 in the “after” models is also set to be 56 seconds. Stage 3 is also set to be the same with the “before” model. Then the main green time for movement 1 is 42 seconds. The signal timing plan is given in Table 5.1.

Table 5.1 Signal Timing Plan for the After Models

Main signal timing plan for after model, 7:00-8:00, @R44/Van Reede Rd					
1	Main signal				
	Mode	Pre-timed			
		stage 1	stage 2	stage 3	
	Green (s)	42	56	28	
	Change Interval (s)	5	6	7	
	Cycle length (s)				144

5.4.2.3 Sorting length

As discussed before, for any given main green time, the optimal sorting length could be determined, and vice versa. In this case, the main right-turn green time reaches a value of 42 seconds in this intersection, which leads to an optimal sorting length of 158 metres (accommodates 22 passenger cars) according to Equation (26). Besides, sorting lengths of 61 metres (8 cars), 82 metres (11 cars), 103 metres (14 cars) and 123 metres (17 cars) are also tested in the “after” models to see how different lengths could affect the approach and the intersection. Signal timing plans for these different sorting areas are given in Table 7.11 (Appendix F).

5.4.2.4 Coordination

The example of a space-time diagram (based on the sorting length of 158 metres) presented in Figure 5.9 shows the coordination between the two signals.

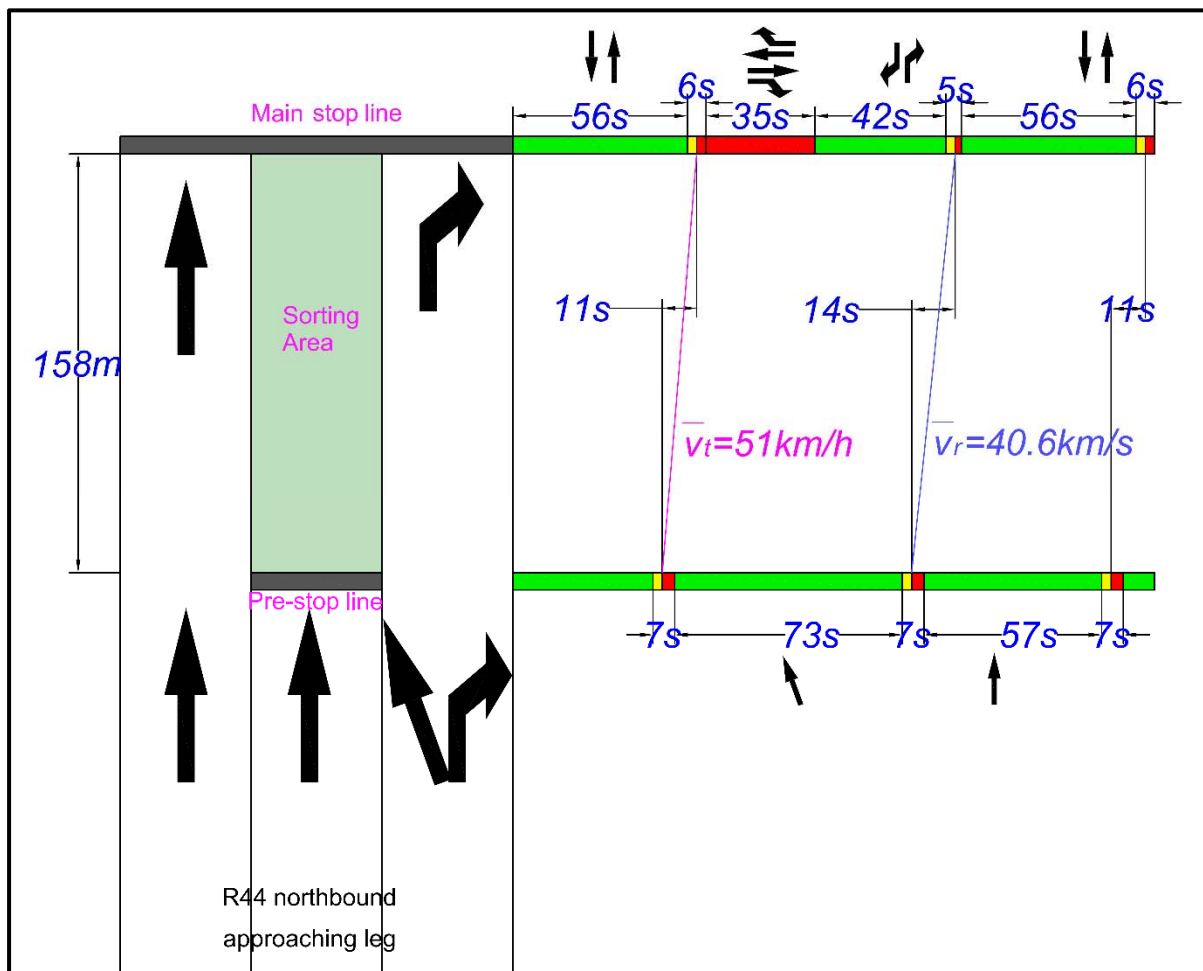


Figure 5.9 Space-Time Diagram of the After Models

5.4.3 Model calibration

The following characteristics of the car following model were calibrated both in the “before” and the “after” models.

- Average jam spacing (6.9m)
- Average total start-up lost time (2.2s)
- Average saturation headway (1.92s)

5.5 Results and discussion

5.5.1 Results

In this section, indexes including capacity benefits, delay, queue length and stop times are compared between the “before” and “after” models.

Table 5.2 Recorded Results of the Before and After Models

Indexes recorded during the one-hour simulation							
AVE STOPS	MOVEMENT	Before	After				
			61m	82m	103m	123m	158m
	1	1.19	0.96	0.76	0.71	0.72	0.71
	2	0.94	0.86	0.83	0.77	0.8	0.79
	3	2.27	0.71	0.71	0.71	0.71	0.71
	4	0.41	0.63	0.63	0.62	0.63	0.63
AVE VEHDELAY(s)	MOVEMENT	Before	After				
			61m	82m	103m	123m	158m
	1	46.2	45.8	44.2	43.8	44.1	44.8
	2	54.6	51.8	50.6	45.8	47.4	47.3
	3	184.7	39.3	39.3	39.3	39.3	39.3
	4	15.2	28.9	28.9	28.8	28.9	28.9
AVE QLEN (m)	QUEUECOUNTER	Before	After				
			61m	82m	103m	123m	158m
	1	116	131	134	128	131	143
	2	301	46	46	46	46	46

5.5.1.1 Capacity benefits

Table 5.3 Capacity Comparison

	BEFORE		AFTER	
MOVEMENT	CAPACITY	GREEN RATIO	CAPACITY	GREEN RATIO
1	703	0.375	973	0.292
2	1709	0.389	-	0.389
3	1107	0.271	1590	0.389
4	1237	0.653	1003	0.535

Table 5.3 presents the capacity comparison for the “before” and “after” models. It should be noted that 1) the capacity of movement 1 in the “after” model used here is the maximum capacity which could be reached when the optimal sorting length (158 metres in this case) is applied; 2) the capacity provided for movement 2 in the “after” model is unknown, further studies on this should be done to study the benefit of the through lane from a sorting area.

It is found that:

- The capacity for movement 1 increases by 270 veh/h while main green time ratio is reduced by 0.085.
- In the “after” model, there are two through lanes at the northbound approach. The simulation shows that the lane designed with sorting area always discharges 1 to 2 more vehicles (when comparing the platoons in the two through lanes passing main stop line with saturation flow) than the through lane without the sorting area. Capacity therefore is increased for the through lane designed with a sorting area. However, capacity lost occurs at the end of the main green. This is because extra sorting area clearance time is allocated to the through vehicles in the “after” models to ensure a cleared sorting area.
- The capacity provided for movement 3 is increased in the “after” models because 17 more seconds of main green time is allocated to it when compared to the “before” model.
- Capacity is reduced from 1237 veh/h to 1003 veh/h for movement 4 because the reduction in green time.

5.5.1.2 Delay

The average vehicle delay in the “before” and “after” models is depicted in Figure 5.10.

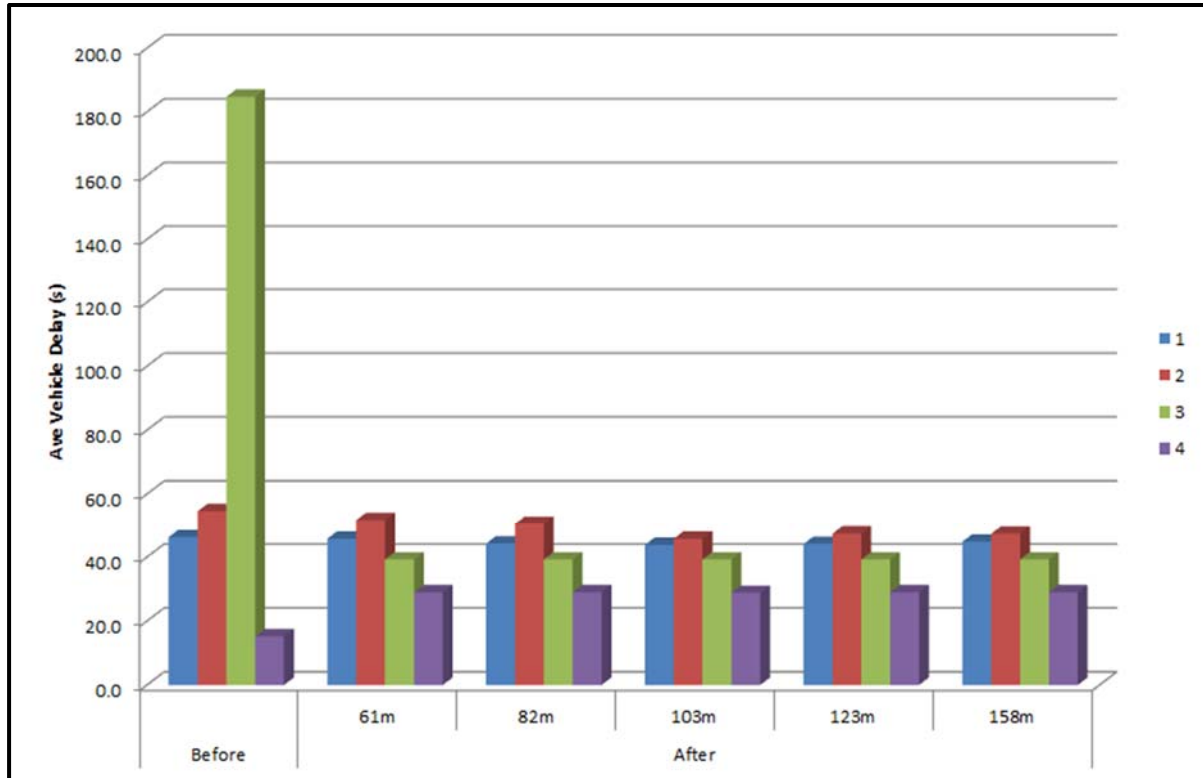


Figure 5.10 Average Vehicle Delay

Comparing the data recorded by the “after” models with the “before” model, the following was observed that:

- Average delay of movement 1 doesn't change much in all the models. However, movement 1 still benefits a lot from the pre-signal system since the green time is reduced from 54 seconds in the “before” model to 42 seconds in the “after” models.
- Average delay of movement 2 decreases after the installation of pre-signal. It decreases as the sorting length increases and reaches the minimum (46 seconds which corresponds to almost 22% reduction in delay) when the sorting length increases to 103 metres. Then, it increases slightly as the sorting length increases.
- For movement 3, average delay reduced significantly from 185 s/veh to 39 s/veh.

- For movement 4, average delay increased from 15 s/veh to 29 s/veh as the green time reduces from 94 seconds to 77 seconds.

5.5.1.3 Average stops

The average vehicle stops recorded in the “before” and “after” models are depicted in Figure 5.11.

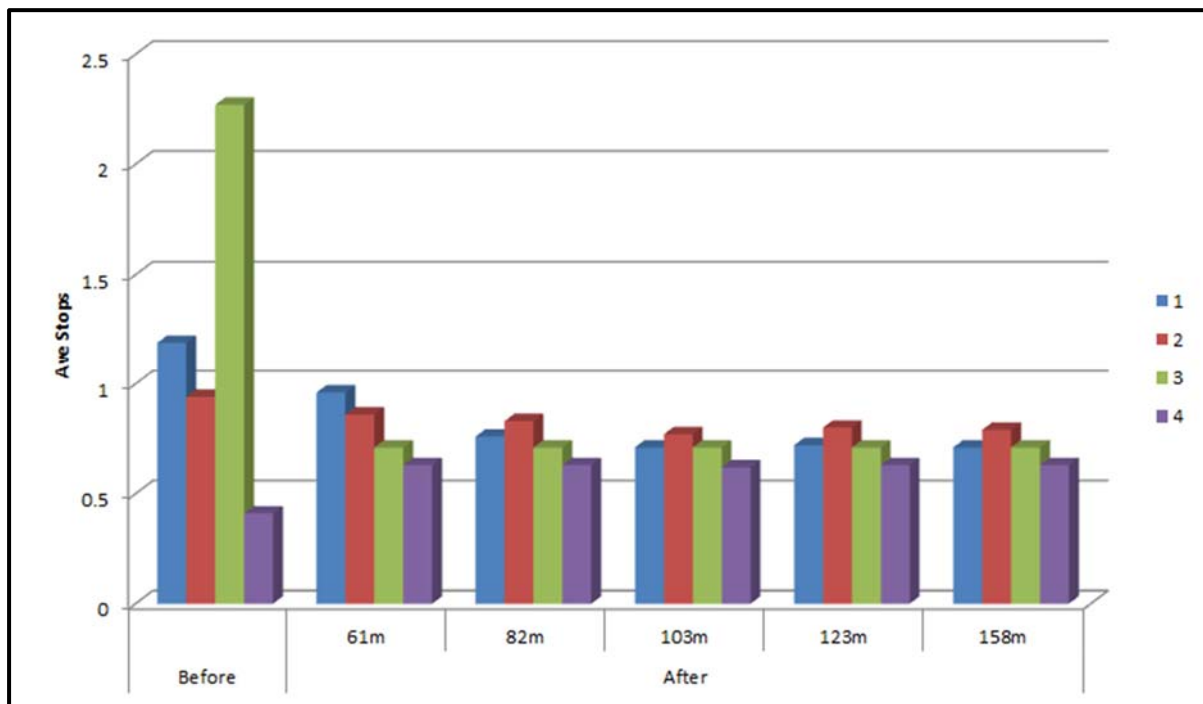


Figure 5.11 Average Vehicle Stops

When comparing the data recorded by the “after” models with the “before” model, it was found that:

- The proposed pre-signal strategy could reduce the average vehicle stops of movement 1 significantly. The average vehicle stops reduce as the sorting length increases and keep the same value after the sorting length reaches a specific value (103 metres in this case).
- It is unexpected that the average vehicle stops of movement 2 reduce as much as 18% in the “after” models with a sorting length of 103 metres.
- Average vehicle stops decrease significantly in movement 3 and increase in movement 4 after the installation of the pre-signal.

5.5.1.4 Queue length

The queue lengths in the “before” and “after” models are depicted in Figure 5.12.

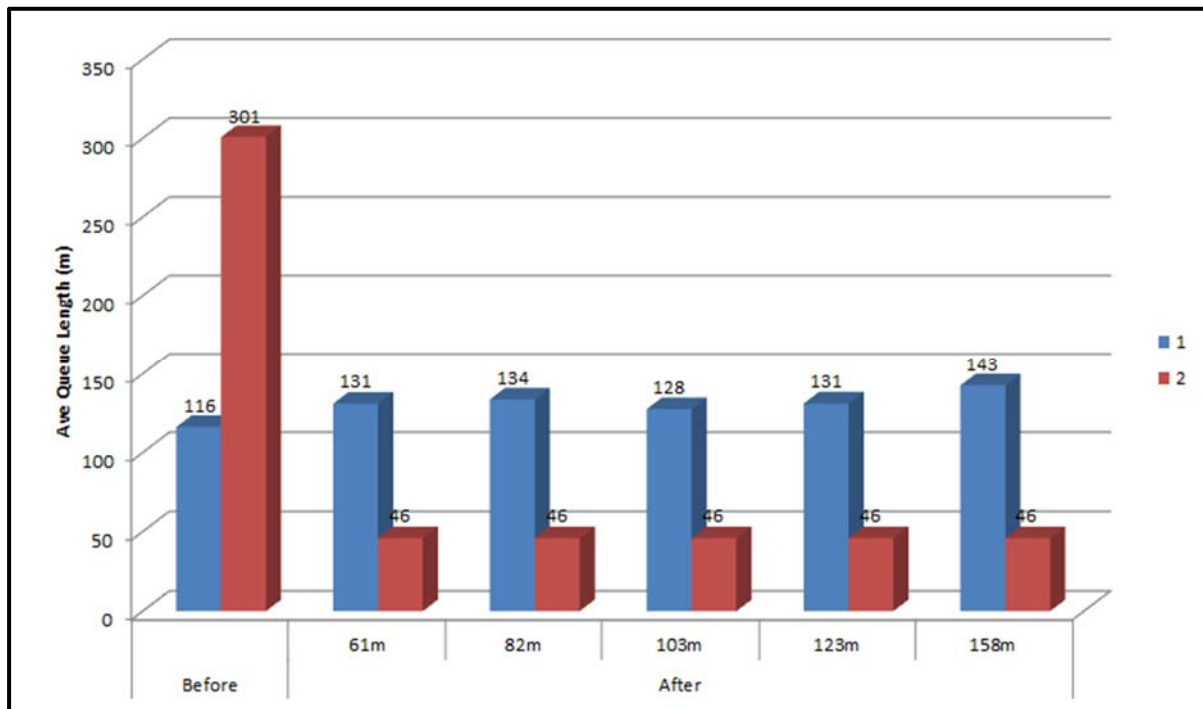


Figure 5.12 Average Queue Lengths

When comparing the data recorded by the “after” models with the “before” model, it was found that:

- Queue length detected by queue counter 1 shows that average queue length increases after the installation of the pre-signal system. It doesn't change much as the sorting length increases. However, it starts to increase after the sorting length reaches 158 metres.
- Queue length detected by queue counter 2 shows that average queue length drops significantly after the installation of the pre-signal system.

5.5.2 Discussion

5.5.2.1 Capacity

As discussed in Section 4.3.2, the right-turn movement could always benefit from the installation of the proposed pre-signal system. The “after” models show that the capacity could be increased by a maximum value of 270veh/h for the given main green time.

The through lane which is designed with a sorting area in the “after” models is found discharging a few more vehicles at the beginning of the main green. It could be because these vehicles are not affected by the start-up lost time when they pass the main stop line.

5.5.2.2 No stopping area

During the simulation, the entrance of the sorting area, where right turn vehicles could make lane changes and enter the sorting area, is sometimes blocked by long vehicles (buses or trucks). In order to prevent this, a no stopping area (marked with a yellow box) as shown in Figure 7.1 is recommended.

5.5.2.3 Sorting length selection

The optimal length of the sorting area in this case study reaches 158 metres, which means the pre-stop line would push the queued through vehicles 158 metres upstream of the main stop line. This could cause some problems, which includes:

- A long sorting area would force the through vehicles to start to queue at the pre-stop line which is far away from the main stop line. It may cause the queued through vehicles blocking (refer to the case of blockage presented in Figure 2.6) right-turn vehicles from entering the right-turn bays or the sorting areas (or forcing the right-turn vehicles to use the right shoulder at a position which is far away from the intersection).
- The success of the coordination between pre-signal and main signal relies on the relatively steady traffic flow. Distance, however, can cause the breakup of platoons due to different travel speeds, truck traffic and other elements (Traffic Engineering Division, 2005), which could potentially undermine the effect of the coordination and cause some vehicles to not clear the sorting area if no additional clearance time was allocated (this additional clearance time leads to the waste of the main green).

Therefore, a long sorting length is not recommended. In this case, the average vehicle delay and average queue length start increasing in the “after” model which installed with a 158-metre long sorting area, which also shows that the benefit decrease after the sorting area reaches a certain length.

5.5.2.4 Delay and stops

- The “after” models show the ability to reduce average vehicle delay and average stops for right-turn turn vehicles. In this case, delay is reduced slightly even when the main green of the right-turn movement is reduced by 12 seconds in the “after” modes.
- It's unexpected that both of the average vehicle delay and average vehicle stops of movement 2 could be reduced as much as 20% after the installation of the pre-signal system. The reason for this is unknown. It is probably and partly because the through vehicles are not affected by the start-up lost time anymore after the installation of the pre-signal and more vehicles could be served during the main green time.
- Movement 3 benefits significantly from the installation of the pre-signal system in this case study. However, this may not be true in reality. A coordinated intersection locating around 400 metres away from this intersection on the north may discharge vehicles to the studied intersection regularly, which would reduce average stops and average vehicle delay. These two indexes may not be as high as those recorded in the “before” model.
- For left-turn movement of the southbound approach, average delay and average stops are increased due to the reduction of green time.

5.5.2.5 Queue length

Queue length of the approaches designed with the proposed pre-signal system are found to be around 13% higher than that of an approach without the pre-signal system. This is probably because the installation of the sorting area consumed part of the space which could be used to store through vehicles. Therefore, attention should be paid to the available stretch of road upstream of the approach before installing the pre-signal strategy.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the analysis and the case study, conclusions are drawn as follows:

- An improved pre-signal concept is proposed in this strategy. Theoretically, the advantages of this control concept when compared to the former ones include:
 - It is specifically designed for right-turn movements;
 - It reduces limitations of the exit lanes;
 - It reduces stop times of the approach;
 - There are more phasing options that could be used in this concept (leading phasing option and phase swapping option); and
 - Shorter time of pre-signal is required to fill the sorting area.
- Main signal green time was derived based on the length of sorting area. Saturation headway and signal timing elements such as start-up lost time, effective green time, clearance lost time, yellow extension and change intervals are considered (refer to Equation(25)).
- Wasted space in the sorting area is studied from a lane change survey at a low speed of 10km/h. It is found that the wasted space is 6.0 metres, 10 metres and 11 metres for lane changes covering 2 lanes, 3 lanes and 4 lanes respectively.
- In order not to waste main green time, pre-signal green time should meet the requirement which is given in Equation(27).
- Sorting area clearance time should be considered when coordinating the pre-signal and the main signal to ensure a cleared sorting area before the main signal serves the next movement. A formula has been derived for through clearance time under specific traffic conditions.
- Leading right-turn phasing option and phase swapping option are found to fit the proposed pre-signal strategy. The leading phasing option, however, has an ability to “feed” more right-turn vehicles into the sorting area because there is more available green time for the pre-signal.

- Based on optimal main green time, the right-turn movement is found to always benefit from the proposed pre-signal strategy. Maximum capacity benefits from the proposed strategy are found to not be significantly affected by the sorting length. However, it increases as the number of sorting lanes and the green ratio increase. Recommended values of expected benefit are given (refer to Table 4.4).
- The right-turn movements benefit significantly from the installation of the proposed pre-signal strategy. Average delay reduces even when the right-turn green time was shorter in the “after” models of the case study.
- The queue length of approaches installed with the proposed pre-signal strategy could be increased. This is probably because the installation of the sorting area consumed part of the space which could be used to store through vehicles.
- The case study showed that through vehicles in the lane where the pre-signal is installed may not be affected by the start-up lost time when passing the main signal if the two signals are coordinated well (this also reduces stop times when compared to the former pre-signal strategy because some of these vehicles only stop once after the pre-stop line). However, capacity reduction does happen at the end of the main green when extra green time has been allocated for clearing the sorting area.

6.2 Recommendations

- Trucks and buses in the traffic flow could undermine the benefits which are derived under traffic conditions with only passenger cars because of their different vehicle attributes. Further studies are recommended to study the proposed pre-signal system on a basis of mixed traffic flow.
- Residue vehicles failed to pass the stop line during main green could be a problem in reality, since this could cause confusion and panic for these drivers. One solution for this could be to force these drivers to go straight if they failed to turn right, for instance. This problem could also lead to safety problems because drivers who fail to pass the stop line in their phase could have a higher rate of violating red.

- In the lane change survey, only 3 drivers and 2 types of cars were tested. The sample size is too small to ensure accurate application. It is just a way to get some rough ideas about the wasted space in a sorting area. Surveys with larger sample size are recommended. Future studies are also recommended to be done on whether it is necessary to provide deceleration distance (as shown in Figure 2.7) for the sorting area.
- This proposed pre-signal strategy is not necessarily restricted by the combination of the two movements which are used as examples in this study, but could also be applied to many situations with different combinations. For example, one could also consider an approach which only has right-turn and left turn lanes in a T-junction.
- Sorting area clearance time still need to be studied by collecting data from real sites.
- It's unexpected that both the average vehicle delay and average vehicle stops of movement 2 are reduced as much as 20% after the installation of the pre-signal system. Further studies on this are recommended.
- A long length for the sorting area is not recommended. Not only because queuing of through vehicles formed after the pre-stop line may block other movements from entering turning bays (e.g., right-turn bays), but also because it could potentially undermine the coordination between the pre-signal and the main signal and cause some vehicles failing to clear the sorting area.
- Average values of some elements of a sorting area were used in this research, which would not be enough for an approach running under the proposed pre-signal strategy in reality. The 85th percentile or even higher values of these elements collected from real sites, for example, could be a better choice to support this study. These elements includes sorting area clearance time, start-up lost time, saturation headway, jam spacing and the extra space required in a sorting area.
- There are several potential problems with this pre-signal strategy. Therefore, trained traffic police are recommended to help organize the traffic in the intersections with newly installed pre-signals.

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CHAPTER 7 APPENDICES

7.1 Appendix A

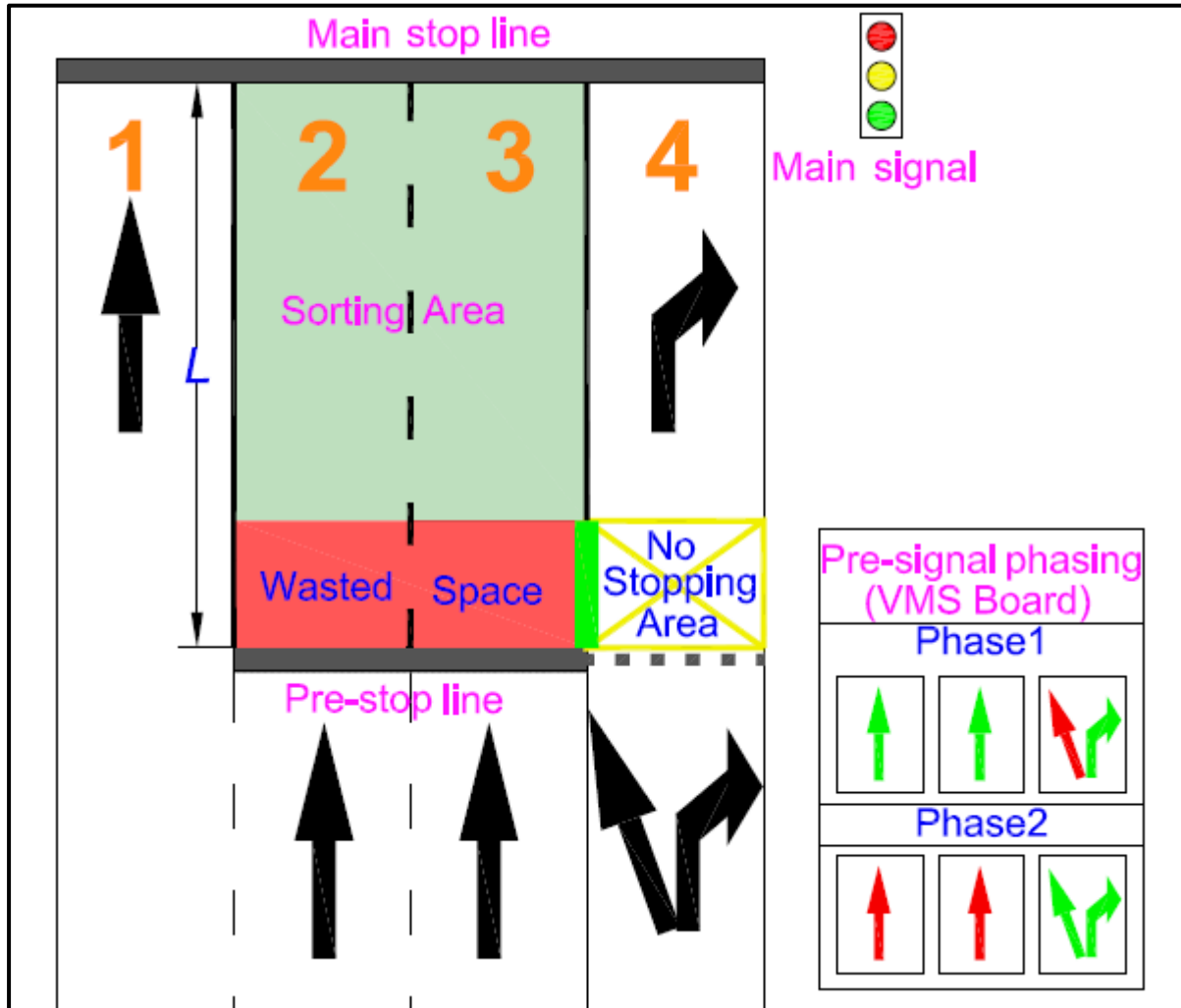


Figure 7.1 Detailed Layout of an Approach Designed with Pre-Signal System

For an approach installed with the proposed pre-signal strategy:

- Additional stop lines which are called “pre-stop lines” would be set upstream of the approach.
- The area created between the two stop line is called “sorting area” where vehicles from different movements are served in turn (Xuan, *et al.*, 2011).
- The sorting area could be designed on part of the through lanes or all of them.
- Additional signals which are called “pre-signals” would be designed to alternate right-of-way for the vehicles held by the pre-stop lines to use the sorting area.

- Through vehicles from the lanes without sorting area are not affected by the pre-signal.
- Right-turn vehicles, only those queuing after the no stopping area, can make lane changes from the right-turn lane to the destination lane in the sorting area when the signal indicates these vehicles to make lane changes. Vehicles queuing between the main stop line and the no stopping area or vehicles from other right-turn lanes which are not neighbouring lanes of the sorting area are forbidden to use the sorting area.
- Through vehicles, only those queuing after the pre-stop line, can enter the sorting area when the pre-signal indicates green to through vehicles. Through vehicles from the other through lanes (if any) are forbidden to make lane changes into the sorting area.
- A no stopping area is marked on the right-turn lane to avoid queued vehicles blocking right-turn vehicles entering the sorting area when they are served by the pre-signal. The length of the no stopping area equals to the length of the wasted area of the sorting area.
- When designing the pre-signals, VMS boards are recommended. Signal should be designed for each lane which is affected by the pre-signal.
- An example of VMS is given in Figure 7.1. It should be noted that the right-turn vehicles are not held by the pre-signal because the pre-signal only control the lane changes of the right-turn vehicles. Right-turn vehicles could always proceed if there is any vacancy ahead in the right-turn lane.

7.2 Appendix B

Table 7.1 Summary of Warrants for Protected Left-turn Mode (1)

Criterion	Warrants		Reference
Delay	LT Delay	≥ 2 vehicle-hours	Agent and Deen 1979, Cottrell 1986, Lalani et al. 1986
	Average LT Delay	≥ 35 s	
Volume	LT Volume	≥ 50 vph	Agent and Deen 1979, Cottrell 1986, ITE 1991, Lalani et al. 1986, Upchurch 1986
		≥ 2 vehicles/cycle	
		> 300 vph	Stamatiadis et al. 1997
		> 320 vph	Asante et al. 1993
		> 50 vph (in one direction)	City of San Diego 2006
	Opposing TH Volume	$> 1,100$ vph	Asante et al. 1993
	Volume Cross Product (Constant)	$> 50,000$ (one opposing lane)	Agent and Deen 1979, ITE 1991, Stamatiadis et al. 1997
		$> 100,000$ (two opposing lanes)	
		$> 144,000$ (two opposing lanes)	Upchurch 1986
		$> 100,000$ (three opposing lanes)	
		$> 100,000$ (one opposing lane)	City of San Diego 2006
	Curve of Left-Turn Threshold Volume versus Opposing Volume	See Figures 9 and 10	Lin and Machemehl 1983
		See Figure 11	Roughail 1986
		See Figure 8	Behnam 1972
Accident/Conflict Experience	LT-Related Accidents	≥ 4 in 1 year, or ≥ 6 in 2 years, or ≥ 8 in 3 years	Agent and Deen 1979, Agent 1987, ITE 1991, Stamatiadis et al. 1997
		≥ 5 in any 12-month period in 3 years	
		≥ 5 per year	City of San Diego 2006
	LT Conflicts	≥ 10 basic conflicts in a peak hour	Agent and Deen 1979
		≥ 14 total conflicts in a peak hour	
		≥ 4 per 100 left-turn vehicles	Cottrell 1986

Note: the word of "left" (or LT) in this figure could be converted to the word of "right" under a left-hand driving rule.

Table 7.2 Summary of Warrants for Protected Left-turn Mode (2)

Criterion	Warrant		Reference
Intersection Geometrics	Sight Distance	≤ 250 ft (opposing speed ≤ 35 mph (75 m) [55 km/h])	ITE 1982, Upchurch 1986, City of San Diego 2006
		≤ 400 ft (opposing speed > 35 mph (120 m) [55 km/h])	
	Number of Opposing TH Lanes	≥ 3	Agent 1987, Asante et al. 1993, Cottrell 1986, City of San Diego 2006
	Number of LT Lanes	≥ 2	Agent 1987, Asante et al. 1993, ITE 1982, City of San Diego 2006
Speed	Opposing Speed	≥ 45 mph (70 km/h)	Agent and Deen 1979, Agent 1987, Asante et al. 1993, Upchurch 1986
Other	Number of Failed Cycles		Fisher 1998
	Benefit/Cost Analysis		Agent and Deen 1979, Cottrell 1986
	Vehicle Queue		Lalani et al. 1986
	LT Storage Length		
	Percent of Heavy Vehicles		
	Political Motivation		
	Public Demand		
	High Truck or Pedestrian Volume		City of San Diego 2006
	50 or More School-Age Pedestrians Crossing the Lane per Hour		
	Access Management Condition		Cottrell 1986
	Angle of the Two Approaches		

Note: the word of "left" (or LT) in this figure could be converted to the word of "right" under a left-hand driving rule.

Table 7.3 Summary of Warrants for Selecting between Protected-Only and Protected/Permissive Phasing Modes

Criterion	Warrant or Guideline		Reference	Recommendation
Delay	LT Delay	≥ 2 vehicle-hours	Cottrell 1986	Install PPLT
	Average LT Delay	≥ 35 s		
Volume (Developed Based on Delay Analysis)	LT Volume	> 50 vph (in one direction)	City of San Diego 2006	Install PO
	Opposing TH Volume	$> 1,000$ vph	Agent 1981	Install PO
	Cross-Volume Product	$> 100,000$ (one opposing lane)	City of San Diego 2006	Install PO
		$200,000 \geq \text{LTOV per lane} \geq 50,000$	Cottrell 1986	Install PPLT
Accident/Conflict Experience	LT-Related Accidents	≥ 4 in 1 year, or ≥ 6 in 2 years, or ≥ 8 in 3 years	Agent 1987, ITE 1991	Install PO
		≥ 5 in any 12-month period in 3 years	City of San Diego 2006	Install PO
		≥ 5 per year		
		≥ 14 total conflicts in a peak hour	Cottrell 1986	Install PO
Intersection Geometrics	Sight Distance	≤ 250 ft (opposing speed ≤ 35 mph) (75 m) [55 km/h]	ITE 1982, Upchurch 1986, City of San Diego 2006	Install PO
		≤ 400 ft (opposing speed > 35 mph) (120 m) [55 km/h]		
	Number of Opposing TH Lanes	≥ 3	Agent 1987, Asante et al. 1993, Cottrell 1986, City of San Diego 2006	Install PO
	Number of LT Lanes	≥ 2	Agent 1987, Asante et al. 1993, ITE 1982, City of San Diego 2006	Install PO
Speed	Opposing Speed	≥ 45 mph (70 km/h)	Agent 1981, Asante et al. 1993, ITE 1982, Upchurch 1986	Install PO
Others	Benefit/Cost Analysis		Agent 1981, Cottrell 1986	Install the One with More Benefit
	High Truck or Pedestrian Volume		Lalani et al. 1986, City of San Diego 2006	Install PO
	50 or More School-Age Pedestrians Crossing the Lane per Hour			
	Access Management Condition		Cottrell 1986	Install PO
Angle of the Two Approaches		Install PO		

Note: the word of "left" (or LT) in this figure could be converted to the word of "right" under a left-hand driving rule.

7.3 Appendix C

Table 7.4 Jam Spacing Survey 1

Morning peak, 7:10-8:30, 10/04/2014, @R44/safraan Rd			
Code	Vehicle number	Queue length (m)	Jam Spacing (m)
1	13	83.7	6.4
2	13	89.3	6.9
3	13	84.2	6.5
4	12	83.6	7.0
5	13	82.8	6.4
6	12	83.2	6.9
7	13	81.3	6.3
8	12	82.1	6.8
9	13	83.5	6.4
10	13	80.3	6.2
11	12	82.0	6.8
12	12	81.1	6.8
13	12	80.2	6.7
14	12	87.5	7.3
15	12	77.3	6.4
16	12	82.0	6.8
17	13	86.8	6.7
18	12	90.2	7.5
19	14	91.8	6.6
20	12	85.5	7.1
21	12	86.0	7.2
22	10	70.5	7.1
23	13	85.1	6.5
24	6	44.2	7.4
25	11	77.6	7.1
26	10	70.1	7.0
27	10	76.4	7.6
28	11	78.4	7.1
29	11	78.3	7.1
30	12	81.2	6.8
31	9	62.3	6.9
32	13	83.4	6.4
33	8	51.9	6.5
34	8	52.8	6.6
35	12	82.9	6.9
36	8	60.4	7.6
37	10	75.6	7.6
Average jam spacing (m)			6.9

Table 7.5 Jam Spacing Survey 2

Afternoon peak, 16:15-17:25, 10/04/2014, @R44/Van Reede Rd			
Code	Vehicle number	Queue length (m)	Jam Spacing (m)
1	13	90.7	7.0
2	11	74.6	6.8
3	13	88.4	6.8
4	11	81.1	7.4
5	13	90.6	7.0
6	13	86.1	6.6
7	13	81.4	6.3
8	12	82.1	6.8
9	12	81.1	6.8
10	12	86.9	7.2
11	13	88.4	6.8
12	11	78.8	7.2
13	13	91.1	7.0
14	13	87.8	6.8
15	12	85.5	7.1
16	12	85.5	7.1
17	12	85.0	7.1
18	13	88.2	6.8
19	8	52.8	6.6
20	12	80.4	6.7
21	12	85.9	7.2
22	12	80.8	6.7
23	13	89.3	6.9
24	13	90.4	7.0
25	13	84.0	6.5
26	11	74.6	6.8
27	13	78.1	6.0
28	12	91.7	7.6
29	13	86.6	6.7
30	12	90.1	7.5
31	13	89.9	6.9
32	12	76.3	6.4
33	12	81.0	6.8
34	11	74.6	6.8
35	13	86.8	6.7
36	11	84.3	7.7
37	10	72.0	7.2
Average jam spacing (m)			6.9

Table 7.6 Jam Spacing Survey 3

Afternoon peak, 16.15-17:25, 10/04/2014, @R44/Van Reede Rd			
Code	Vehicle number	Queue length (m)	Jam Spacing (m)
1	12	84.8	7.1
2	12	84.7	7.1
3	13	85.0	6.5
4	13	85.9	6.6
5	13	87.4	6.7
6	13	89.0	6.8
7	10	75.4	7.5
8	13	87.8	6.8
9	13	86.4	6.6
10	13	88.1	6.8
11	12	89.0	7.4
12	13	91.5	7.0
13	13	91.9	7.1
14	13	89.4	6.9
15	12	80.6	6.7
16	14	85.6	6.1
17	12	86.0	7.2
18	12	84.5	7.0
19	12	89.5	7.5
20	13	89.0	6.8
21	13	85.8	6.6
22	12	81.8	6.8
23	13	85.7	6.6
24	12	89.6	7.5
25	13	89.5	6.9
26	13	89.6	6.9
27	13	89.2	6.9
28	14	88.9	6.4
29	13	90.4	7.0
30	13	86.3	6.6
31	12	85.6	7.1
32	12	87.1	7.3
33	12	84.5	7.0
34	12	89.2	7.4
35	14	88.1	6.3
36	13	89.3	6.9
37	12	87.2	7.3
Average jam spacing (m)			6.9

7.4 Appendix D

Table 7.7 Data of Lane Change Survey

13:30~16:30, 30/03/2014, @ Parking lot of the Engineering Faculty									
	Name		Driving mileage (km)		Licensed at		Driving years		
Driver A	Rui Zhang		39000		Feb., 2012		2		
Driver B	Jason Wang		21000		July, 2011		2.5		
Driver C	Ray Zhu		5000		July, 2013		0.5		
Speed (km/h)		around 10							
Vehicle mode				4.7-metre long Audi A4					
	Covering 2 lanes (m)			Covering 3 lanes (m)			Covering 4 lanes (m)		
<div>Drivers No.</div>	A	B	C	A	B	C	A	B	C
1	4.8	6.9	4.3	9.5	10.1	9.9	10.4	11.4	9.7
2	5.3	7.0	5.5	9.1	11.1	9.6	10.1	11.1	11.2
3	4.9	6.6	7.0	9.6	10.8	10.2	9.2	11.6	10.3
4	5.6	5.9	6.5	10.0	12.9	10.4	9.9	12.4	11.8
5	5.7	6.2	8.8	9.4	12.3	10.2	9.9	11.9	10.6
I_w	5.3	6.5	6.4	9.5	11.4	10.1	9.9	11.7	10.7
L_w	6.1			10.3			10.8		
Vehicle mode				3.6-metre long Ford KA					
	Covering 2 lanes (m)			Covering 3 lanes (m)			Covering 4 lanes (m)		
<div>Drivers No.</div>	A	B	C	A	B	C	A	B	C
1	4.8	6.1	5.3	9.0	10.3	8.4	10.7	10.4	10.5
2	6.7	6.7	5.8	9.0	10.3	8.4	11.0	10.9	11.0
3	5.9	6.1	6.0	9.8	10.3	9.0	9.7	11.5	11.1
4	6.6	6.6	5.9	9.3	9.0	8.2	11.1	10.3	10.9
5	5.1	5.9	5.8	9.9	9.5	8.3	10.6	9.7	9.4
I_w	5.8	6.3	5.8	9.4	9.9	8.5	10.6	10.6	10.6
L_w	6.0			9.2			10.6		

Table 7.9 Traffic Counts of R44/Van Reede Rd 1

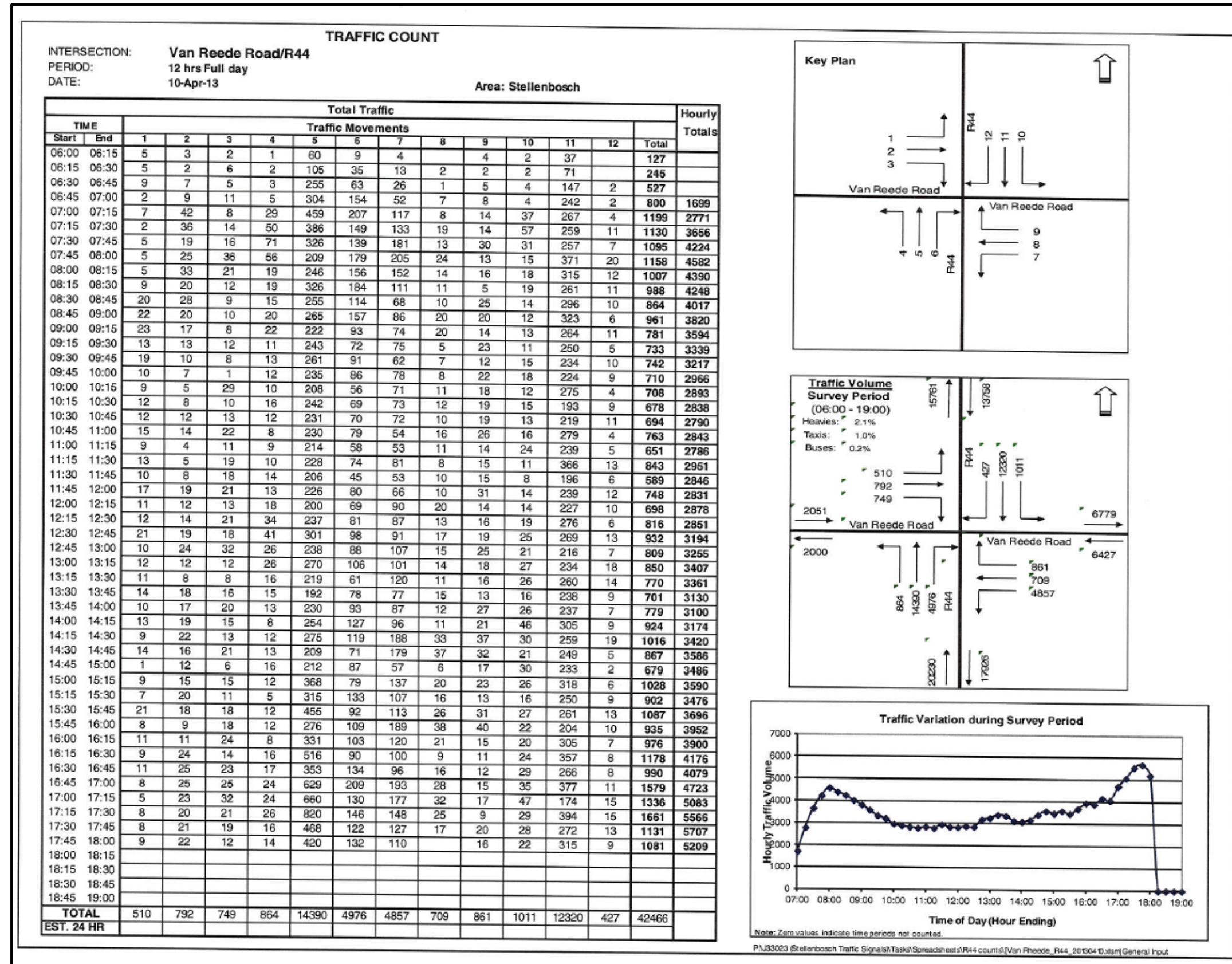


Table 7.10 Traffic Counts of R44/Van Reede Rd 2

TRAFFIC COUNT															
INTERSECTION:		Van Reede Road/R44													
PERIOD:		12 hrs Full day													
DATE:		10-Apr-13													
Area: Stellenbosch															
TIME		Total Traffic												Hourly Totals	
Start	End	Traffic Movements													
		1	2	3	4	5	6	7	8	9	10	11	12		Total
06:00	06:15	5	3	2	1	60	9	4		4	2	37		127	127
06:15	06:30	5	2	6	2	105	35	13	2	2	2	71		245	372
06:30	06:45	9	7	5	3	255	63	26	1	5	4	147	2	527	899
06:45	07:00	2	9	11	5	304	154	52	7	8	4	242	2	800	1699
07:00	07:15	7	42	8	29	459	207	117	8	14	37	267	4	1199	2771
07:15	07:30	2	36	14	50	386	149	133	19	14	57	259	11	1130	3656
07:30	07:45	5	19	16	71	326	139	181	13	30	31	257	7	1095	4224
07:45	08:00	5	25	36	56	209	179	205	24	13	15	371	20	1158	4582
08:00	08:15	5	33	21	19	246	156	152	14	16	18	315	12	1007	4390
08:15	08:30	9	20	12	19	326	184	111	11	5	19	261	11	988	4248
08:30	08:45	20	28	9	15	255	114	68	10	25	14	296	10	864	4017
08:45	09:00	22	20	10	20	265	157	86	20	20	12	323	6	961	3820
09:00	09:15	23	17	8	22	222	93	74	20	14	13	264	11	781	3594
09:15	09:30	13	13	12	11	243	72	75	5	23	11	250	5	733	3339
09:30	09:45	19	10	8	13	261	91	62	7	12	15	234	10	742	3217
09:45	10:00	10	7	1	12	235	86	78	8	22	18	224	9	710	2966
10:00	10:15	9	5	29	10	208	56	71	11	18	12	275	4	708	2893
10:15	10:30	12	8	10	16	242	69	73	12	19	15	193	9	678	2838
10:30	10:45	12	12	13	12	231	70	72	10	19	13	219	11	694	2790
10:45	11:00	15	14	22	8	230	79	54	16	26	16	279	4	763	2843
11:00	11:15	9	4	11	9	214	58	53	11	14	24	239	5	651	2786
11:15	11:30	13	5	19	10	228	74	81	8	15	11	366	13	843	2951
11:30	11:45	10	8	18	14	206	45	53	10	15	8	196	6	589	2846
11:45	12:00	17	19	21	13	226	80	66	10	31	14	239	12	748	2831
12:00	12:15	11	12	13	18	200	69	90	20	14	14	227	10	698	2878
12:15	12:30	12	14	21	34	237	81	87	13	16	19	276	6	816	2851
12:30	12:45	21	19	18	41	301	98	91	17	19	25	269	13	932	3194
12:45	13:00	10	24	32	26	238	88	107	15	25	21	216	7	809	3255
13:00	13:15	12	12	12	26	270	106	101	14	18	27	234	18	850	3407
13:15	13:30	11	8	8	16	219	61	120	11	16	26	260	14	770	3361
13:30	13:45	14	18	16	15	192	78	77	15	13	16	238	9	701	3130
13:45	14:00	10	17	20	13	230	93	87	12	27	26	237	7	779	3100
14:00	14:15	13	19	15	8	254	127	96	11	21	46	305	9	924	3174
14:15	14:30	9	22	13	12	275	119	188	33	37	30	259	19	1016	3420
14:30	14:45	14	16	21	13	209	71	179	37	32	21	249	5	867	3586
14:45	15:00	1	12	6	16	212	87	57	6	17	30	233	2	679	3486
15:00	15:15	9	15	15	12	368	79	137	20	23	26	318	6	1028	3590
15:15	15:30	7	20	11	5	315	133	107	16	13	16	250	9	902	3476
15:30	15:45	21	18	18	12	455	92	113	26	31	27	261	13	1087	3696
15:45	16:00	8	9	18	12	276	109	189	38	40	22	204	10	935	3952
16:00	16:15	11	11	24	8	331	103	120	21	15	20	305	7	976	3900
16:15	16:30	9	24	14	16	516	90	100	9	11	24	357	8	1178	4176
16:30	16:45	11	25	23	17	353	134	96	16	12	29	266	8	990	4079
16:45	17:00	8	25	25	24	629	209	193	28	15	35	377	11	1579	4723
17:00	17:15	5	23	32	24	660	130	177	32	17	47	174	15	1336	5083
17:15	17:30	8	20	21	26	820	146	148	25	9	29	394	15	1661	5566
17:30	17:45	8	21	19	16	468	122	127	17	20	28	272	13	1131	5707
17:45	18:00	9	22	12	14	420	132	110		16	22	315	9	1081	5209
18:00	18:15														3873
18:15	18:30														2212
18:30	18:45														1081
18:45	19:00														
TOTAL		510	792	749	864	14390	4976	4857	709	861	1011	12320	427	42466	
EST. 24 HR															

Key Plan

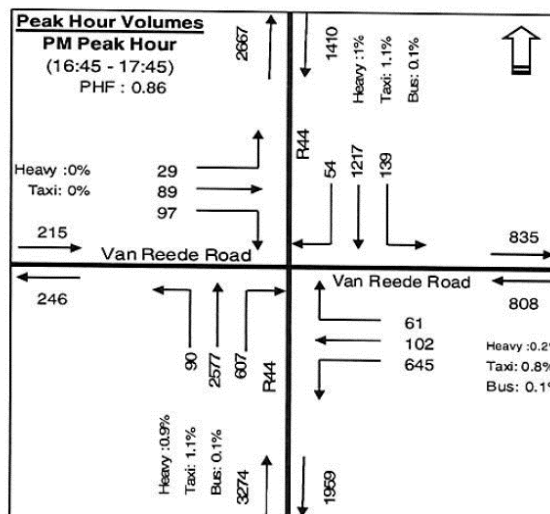
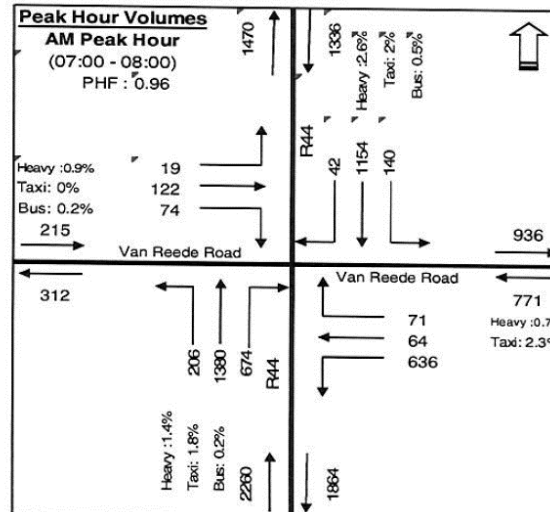
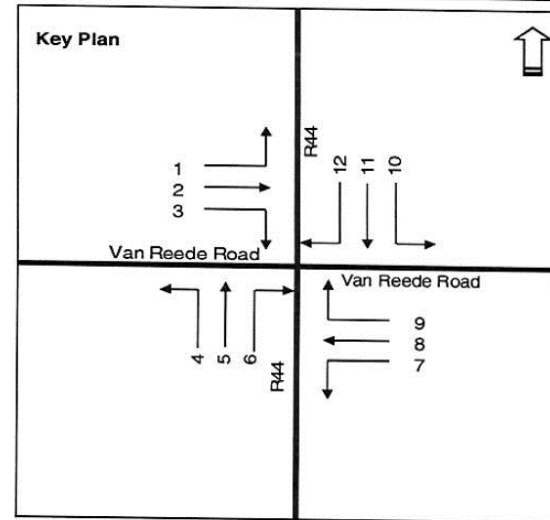
Peak Hour Volumes

AM Peak Hour
(07:00 - 08:00)
PHF : 0.96

Peak Hour Volumes

PM Peak Hour
(16:45 - 17:45)
PHF : 0.86

P:\J33023 (Stellenbosch Traffic Signals)\Tasks\Spreadsheets\R44 counts\Van Rneede_R44_20\30410.xlsm\General Input



P:\J33023 (Stellenbosch Traffic Signals)\Task\Spreadsheets\R44 counts\Van Reede_R44_20130410.xlsx\General Input

7.6 Appendix F

Table 7.11 Pre-Signal Timing Plans for Different Sorting Lengths

Pre-signal timing plan for after model, 7:00-8:00, @R44/Van Reede Rd				
1	Pre-signal_61m			
	Mode	Pre-timed		
		stage 1	stage 2	
	Green (s)	74	57	
	Change Interval (s)	6	7	
	Cycle length (s)			144
	Sorting area			
	Clearance time (s)	8	5	
2	Pre-signal_82m			
	Mode	Pre-timed		
		stage 1	stage 2	
	Green (s)	72	57	
	Change Interval (s)	8	7	
	Cycle length (s)			144
	Sorting area			
	Clearance time (s)	10	6	
3	Pre-signal_103			
	Mode	Pre-timed		
		stage 1	stage 2	
	Green (s)	72	57	
	Change Interval (s)	8	7	
	Cycle length (s)			144
	Sorting area			
	Clearance time (s)	11	7	
4	Pre-signal_123m			
	Mode	Pre-timed		
		stage 1	stage 2	
	Green (s)	72	57	
	Change Interval (s)	8	7	
	Cycle length (s)			144
	Sorting area			
	Clearance time (s)	12	8	
5	Pre-signal_158m			
	Mode	Pre-timed		
		stage 1	stage 2	
	Green (s)	73	57	
	Change Interval (s)	7	7	
	Cycle length (s)			144
	Sorting area			
	Clearance time (s)	14	11	